Higgs Physics, Supersymmetry and Future Colliders

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Next Step in the Energy Frontier
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Going Beyond the SM :
Two Higgs Doublet Models

- The simplest extension of the SM is to add one Higgs doublet, with the same quantum numbers as the SM one.

- Now, we will have contributions to the gauge boson masses coming from the vacuum expectation value of both fields

$$(\mathcal{D}\phi_i)^\dagger \mathcal{D}\phi_i \to g^2 \phi_i^\dagger T^a T^b \phi_i A_\mu^a A^{\mu,b}$$

- Therefore, the gauge boson masses are obtained from the SM expressions by simply replacing

$$v^2 \to v_1^2 \ + \ v_2^2$$

- There is then a free parameter, that is the ratio of the two vacuum expectation values, and this is usually denoted by

$$\tan\beta = \frac{v_2}{v_1}$$

- The number of would-be Goldstone modes are the same as in the SM, namely 3. Therefore, there are still 5 physical degrees of freedom in the scalar sector which are a charged Higgs, a CP-odd Higgs and two CP-even Higgs bosons.

CP-even Higgs Bosons

- There is no symmetry argument and in general these two Higgs boson states will mix. The mass eigenvalues, in increasing order of mass, will be

$$\sqrt{2}\;\; h = -\sin\alpha \;\; \mathrm{Re}H_1^0 + \cos\alpha \;\; \mathrm{Re}H_2^0$$
$$\sqrt{2}\;\; H = \cos\alpha \;\; \mathrm{Re}H_1^0 + \sin\alpha \;\; \mathrm{Re}H_2^0$$

- From here one can easily obtain the coupling to the gauge bosons. This is simply given by replacing in the mass contributions

$$v_i \rightarrow v_i + ReH_i^0$$

- This leads to a coupling to gauge bosons proportional to

$$v_i \;\; \mathrm{Re}H_i^0$$

- Hence, the effective coupling of h is given by

$$hVV = (hVV)^{\mathrm{SM}}(-\cos\beta\sin\alpha + \sin\beta\cos\alpha) = (hVV)^{\mathrm{SM}}\sin(\beta-\alpha)$$
$$HVV = (hVV)^{\mathrm{SM}}(\cos\beta\cos\alpha + \sin\beta\sin\alpha) = (hVV)^{\mathrm{SM}}\cos(\beta-\alpha)$$

- These proportionality factors are nothing but the projection of the Higgs mass eigenstates into the one acquiring a vacuum expectation value.

Low Energy Supersymmetry : Type II Higgs doublet models

- In Type II models, the Higgs H1 would couple to down-quarks and charge leptons, while the Higgs H2 couples to up quarks and neutrinos. Therefore,

$$g_{hff}^{dd,ll} = \frac{\mathcal{M}_{dd,ll}^{\rm diag}}{v} \frac{(-\sin\alpha)}{\cos\beta}, \qquad g_{Hff}^{dd,ll} = \frac{\mathcal{M}_{dd,ll}^{\rm diag}}{v} \frac{\cos\alpha}{\cos\beta}$$

$$g_{hff}^{uu} = \frac{\mathcal{M}_{uu}^{\rm diag}}{v} \frac{(\cos\alpha)}{\sin\beta}, \qquad g_{Hff}^{uu} = \frac{\mathcal{M}_{uu}^{\rm diag}}{v} \frac{\sin\alpha}{\sin\beta}$$

- If the mixing is such that

$$\sin\alpha = -\cos\beta,$$
$$\cos\alpha = \sin\beta$$

then the coupling of the lightest Higgs to fermions and gauge bosons is SM-like. This limit is called decoupling limit. Is it possible to obtain similar relations for lower values of the CP-odd Higgs mass ? We shall call this situation ALIGNMENT

- Observe that close to the decoupling limit, the lightest Higgs couplings are SM-like, while the heavy Higgs couplings to down quarks and up quarks are enhanced (suppressed) by a $\tan\beta$ factor. We shall concentrate on this case.

- It is important to stress that the coupling of the CP-odd Higgs boson

$$g_{Aff}^{dd,ll} = \frac{\mathcal{M}_{\rm diag}^{\rm dd}}{v} \tan\beta, \qquad g_{Aff}^{uu} = \frac{\mathcal{M}_{\rm diag}^{\rm uu}}{v\tan\beta}$$

Alignment in General two Higgs Doublet Models

H. Haber and J. Gunion'03

$$
\begin{aligned}
V \;=\;& m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + \mathrm{h.c.}) + \frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 \\
& +\lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) \\
& + \left\{\frac{1}{2}\lambda_5(\Phi_1^\dagger\Phi_2)^2 + [\lambda_6(\Phi_1^\dagger\Phi_1) + \lambda_7(\Phi_2^\dagger\Phi_2)]\Phi_1^\dagger\Phi_2 + \mathrm{h.c.}\right\} \;,
\end{aligned}
$$

- From here, one can minimize the effective potential and derive the expression for the CP-even Higgs mass matrix in terms of a reference mass, that we will take to be mA

Carena, Low, Shah, C.W.'13

$$
\mathcal{M} = \begin{pmatrix} \mathcal{M}_{11} & \mathcal{M}_{12} \\ \mathcal{M}_{12} & \mathcal{M}_{22} \end{pmatrix} \equiv m_A^2 \begin{pmatrix} s_\beta^2 & -s_\beta c_\beta \\ -s_\beta c_\beta & c_\beta^2 \end{pmatrix} + v^2 \begin{pmatrix} L_{11} & L_{12} \\ L_{12} & L_{22} \end{pmatrix}
$$

$$
\begin{aligned}
L_{11} &= \lambda_1 c_\beta^2 + 2\lambda_6 s_\beta c_\beta + \lambda_5 s_\beta^2 \;, \\
L_{12} &= (\lambda_3 + \lambda_4) s_\beta c_\beta + \lambda_6 c_\beta^2 + \lambda_7 s_\beta^2 \;, \\
L_{22} &= \lambda_2 s_\beta^2 + 2\lambda_7 s_\beta c_\beta + \lambda_5 c_\beta^2 \;.
\end{aligned}
$$

CP-even Higgs Mixing Angle and Alignment

M. Carena, I. Low, N. Shah, C.W.', arXiv:1310.2248

$$\sin\alpha = \frac{\mathcal{M}_{12}^2}{\sqrt{\mathcal{M}_{12}^4 + \left(\mathcal{M}_{11}^2 - m_h^2\right)^2}}$$

$$-\tan\beta\ \mathcal{M}_{12}^2 = \left(\mathcal{M}_{11}^2 - m_h^2\right) \longrightarrow \sin\alpha = -\cos\beta$$

Condition independent of the CP-odd Higgs mass.

$$\begin{pmatrix} s_\beta^2 & -s_\beta c_\beta \\ -s_\beta c_\beta & c_\beta^2 \end{pmatrix} \begin{pmatrix} -s_\alpha \\ c_\alpha \end{pmatrix} = -\frac{v^2}{m_A^2} \begin{pmatrix} L_{11} & L_{12} \\ L_{12} & L_{22} \end{pmatrix} \begin{pmatrix} -s_\alpha \\ c_\alpha \end{pmatrix} + \frac{m_h^2}{m_A^2} \begin{pmatrix} -s_\alpha \\ c_\alpha \end{pmatrix}$$

M. Carena, I. Low, N. Shah, C.W.'13

Alignment Conditions

$$(m_h^2 - \lambda_1 v^2) + (m_h^2 - \tilde{\lambda}_3 v^2) t_\beta^2 = v^2 (3\lambda_6 t_\beta + \lambda_7 t_\beta^3) \ ,$$

$$(m_h^2 - \lambda_2 v^2) + (m_h^2 - \tilde{\lambda}_3 v^2) t_\beta^{-2} = v^2 (3\lambda_7 t_\beta^{-1} + \lambda_6 t_\beta^{-3})$$

- If fulfilled not only alignment is obtained, but also the right Higgs mass, $m_h^2 = \lambda_{\rm SM} v^2$, with $\lambda_{\rm SM} \simeq 0.26$ and $\lambda_3 + \lambda_4 + \lambda_5 = \tilde{\lambda}_3$

$$\lambda_{\rm SM} = \lambda_1 \cos^4\beta + 4\lambda_6 \cos^3\beta \sin\beta + 2\tilde{\lambda}_3 \sin^2\beta \cos^2\beta + 4\lambda_7 \sin^3\beta \cos\beta + \lambda_2 \sin^4\beta$$

- For $\lambda_6 = \lambda_7 = 0$ the conditions simplify, but can only be fulfilled if

$$\lambda_1 \ \geq \ \lambda_{\rm SM} \ \geq \ \tilde{\lambda}_3 \quad \text{and} \quad \lambda_2 \ \geq \ \lambda_{\rm SM} \ \geq \ \tilde{\lambda}_3 \ ,$$

or

$$\lambda_1 \ \leq \ \lambda_{\rm SM} \ \leq \ \tilde{\lambda}_3 \quad \text{and} \quad \lambda_2 \ \leq \ \lambda_{\rm SM} \ \leq \ \tilde{\lambda}_3$$

- Conditions not fulfilled in the MSSM, where both $\lambda_1, \tilde{\lambda}_3 < \lambda_{\rm SM}$

Deviations from Alignment

$$c_{\beta-\alpha} = t_\beta^{-1}\eta \ , \qquad s_{\beta-\alpha} = \sqrt{1 - t_\beta^{-2}\eta^2}$$

The couplings of down fermions are not only the ones that dominate the Higgs width but also tend to be the ones which differ at most from the SM ones

$$g_{hVV} \approx \left(1 - \frac{1}{2}t_\beta^{-2}\eta^2\right) g_V \ , \qquad g_{HVV} \approx t_\beta^{-1}\eta \ g_V \ ,$$

$$g_{hdd} \approx (1-\eta)\, g_f \ , \qquad g_{Hdd} \approx t_\beta(1 + t_\beta^{-2}\eta) g_f$$

$$g_{huu} \approx (1 + t_\beta^{-2}\eta)\, g_f \ , \qquad g_{Huu} \approx -t_\beta^{-1}(1-\eta) g_f$$

For small departures from alignment, the parameter η can be determined as a function of the quartic couplings and the Higgs masses

$$\eta = s_\beta^2\left(1 - \frac{\mathcal{A}}{\mathcal{B}}\right) = s_\beta^2\frac{\mathcal{B}-\mathcal{A}}{\mathcal{B}}, \qquad \mathcal{B} - \mathcal{A} = \frac{1}{s_\beta}\left(-m_h^2 + \tilde{\lambda}_3 v^2 s_\beta^2 + \lambda_7 v^2 s_\beta^2 t_\beta + 3\lambda_6 v^2 s_\beta c_\beta + \lambda_1 v^2 c_\beta^2\right)$$

$$\mathcal{B} = \frac{\tilde{\mathcal{M}}_{11}^2 - m_h^2}{s_\beta} = \left(m_A^2 + \lambda_5 v^2\right) s_\beta + \lambda_1 v^2 \frac{c_\beta}{t_\beta} + 2\lambda_6 v^2 c_\beta - \frac{m_h^2}{s_\beta}$$

Low Energy Supersymmetry

- Tree-level : Type II two Higgs Doublet Model

At the quantum level :

- Quartic Couplings determined as a function of gauge and Yukawa couplings and the supersymmetric spectrum
- Couplings to fermions receive corrections that go beyond the type II structure. These corrections are loop suppressed and do not affect the overall type II FCNC suppression mechanism.
- Contributions to flavor processes depend strongly on third generation supersymmetry breaking parameters as well as on flavor structure of mass parameters. Small deviations from scalar mass flavor independence can have a strong impact on flavor processes, but a weak one on Higgs physics and therefore we will not discuss flavor physics constraints.

Lightest SM-like Higgs mass strongly depends on:

* CP-odd Higgs mass m_A
* tan beta
* the top quark mass
* the stop masses and mixing

$$\mathbf{M}^2_{\tilde{t}} = \begin{pmatrix} m_Q^2 + m_t^2 + D_L & m_t X_t \\ m_t X_t & m_U^2 + m_t^2 + D_R \end{pmatrix}$$

M_h depends logarithmically on the averaged stop mass scale M_{SUSY} and has a quadratic and quartic dep. on the stop mixing parameter X_t. [and on sbotton/stau sectors for large tanbeta]

For moderate to large values of tan beta and large non-standard Higgs masses

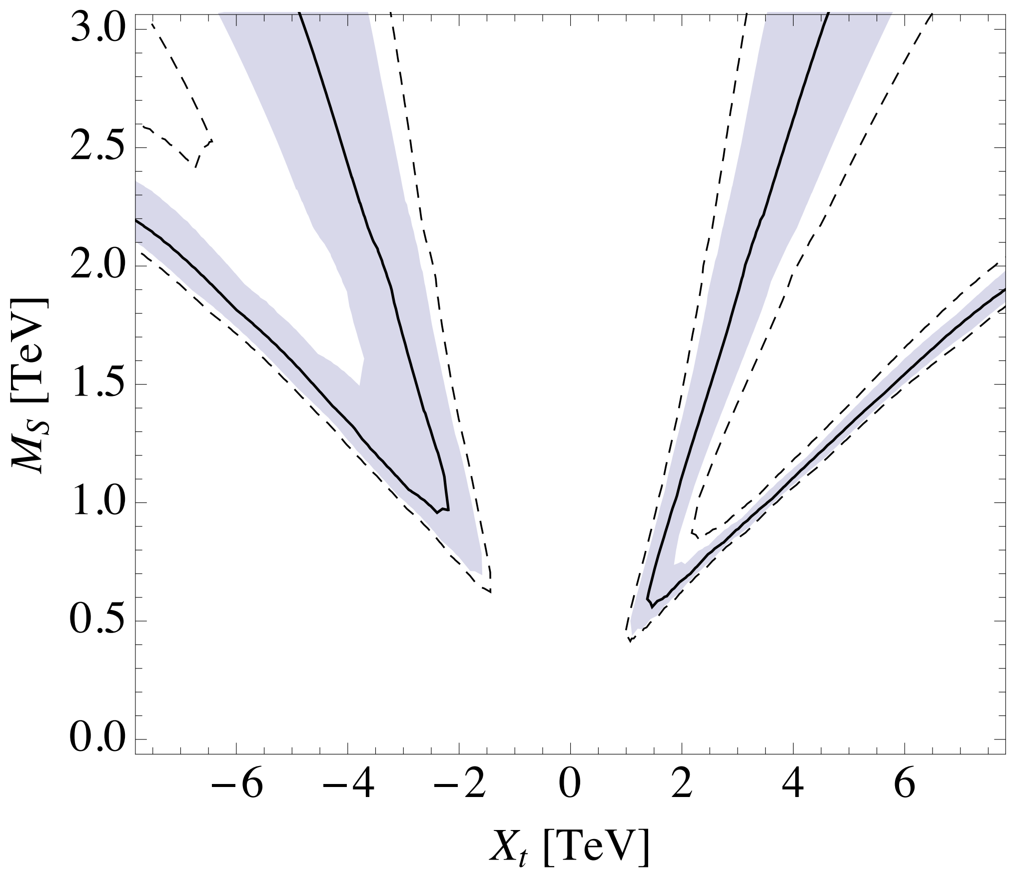
$$\boxed{m_h^2 \cong M_Z^2 \cos^2 2\beta + \frac{3}{4\pi^2}\frac{m_t^4}{\mathrm{v}^2}\left[\frac{1}{2}\tilde{X}_t + t + \frac{1}{16\pi^2}\left(\frac{3}{2}\frac{m_t^2}{\mathrm{v}^2} - 32\pi\alpha_3\right)\left(\tilde{X}_t t + t^2\right)\right]}$$

$$t = \log(M_{SUSY}^2 / m_t^2) \qquad \tilde{X}_t = \frac{2X_t^2}{M_{SUSY}^2}\left(1 - \frac{X_t^2}{12 M_{SUSY}^2}\right) \qquad X_t = A_t - \mu/\tan\beta \rightarrow \text{LR stop mixing}$$

M.Carena, J.R. Espinosa, M. Quiros, C.W.'95
M. Carena, M. Quiros, C.W.'95

Analytic expression valid for $M_{SUSY} \sim m_Q \sim m_U$

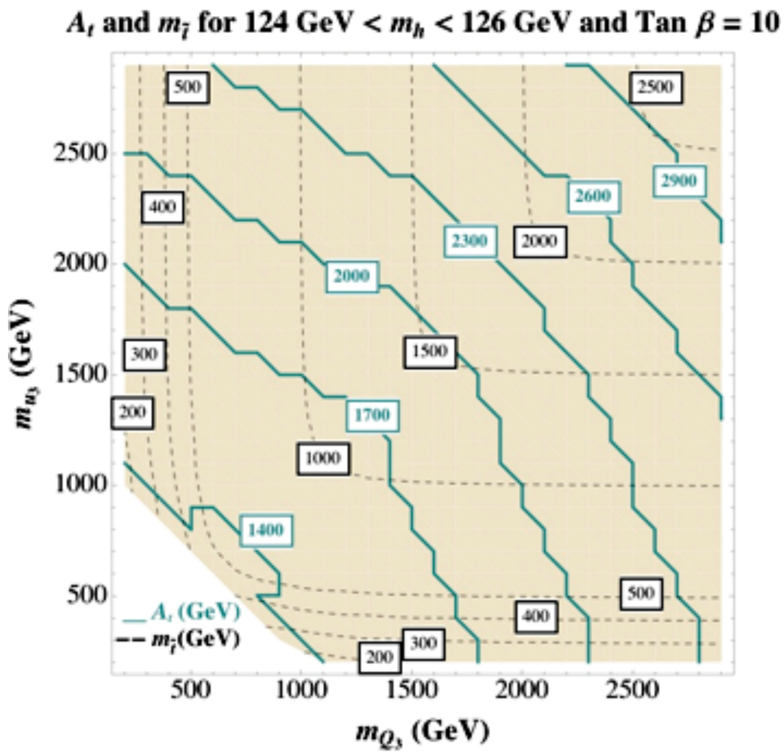
Large Mixing in the Stop Sector Necessary

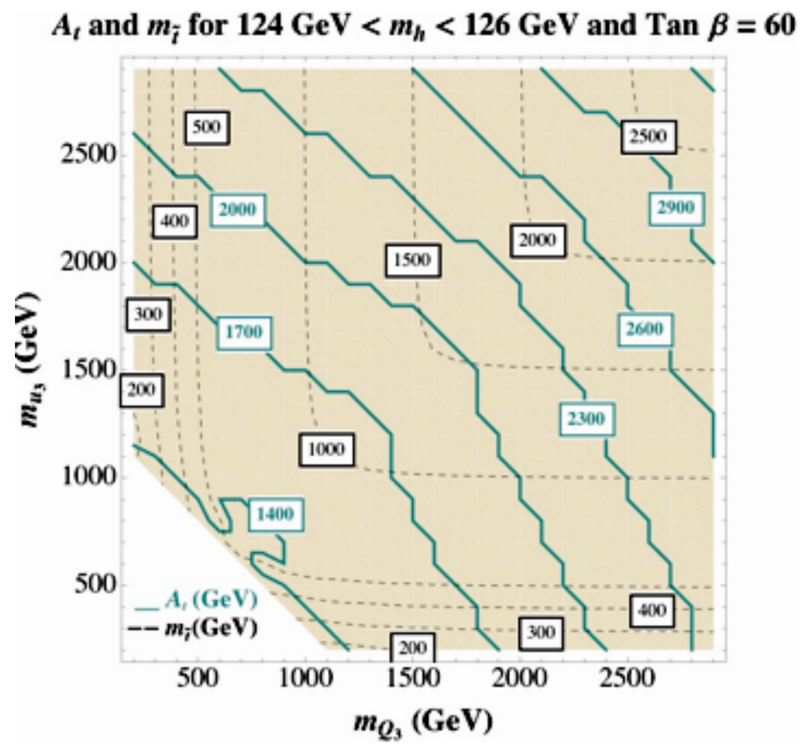


P. Draper, P. Meade, M. Reece, D. Shih'11
L. Hall, D. Pinner, J. Ruderman'11
M. Carena, S. Gori, N. Shah, C. Wagner'11
A. Arbey, M. Battaglia, A. Djouadi, F. Mahmoudi, J. Quevillon'11
S. Heinemeyer, O. Stal, G. Weiglein'11
U. Ellwanger'11

Soft supersymmetry Breaking Parameters

M. Carena, S. Gori, N. Shah, C. Wagner, arXiv:1112.336, +L.T.Wang, arXiv:1205.5842





Large stop sector mixing
A_t > 1 TeV

No lower bound on the lightest stop
One stop can be light and the other heavy
or
in the case of similar stop soft masses.
both stops can be below 1TeV

Intermediate values of tan beta lead to
the largest values of m_h for the same values
of stop mass parameters

At large tan beta, light staus/sbottoms can decrease
mh by several GeV's via Higgs mixing effects
and compensate tan beta enhancement

Stop Mixing and the Stop Mass Scale

- For smaller values of the mixing parameter, the Stop Mass Scale must be pushed to values (far) above the TeV scale

- The same is true for smaller values of $\tan\beta$, for which the tree-level contribution is reduced

- In these cases, the RG approach allows to resum the large logarithmic corrections and leads to a more precise determination of the Higgs mass than the fixed order computations.

- The level of accuracy may be increased by including weak coupling corrections to both the RG running of the quartic coupling, as well as threshold corrections that depend on these couplings

- One can also use the RG approach to obtain partial results at a given fixed order by the methods we shall describe below

Draper, Lee, C.W. '13

The analysis of the three-loop corrections show a high degree of cancellation between the dominant and subdominant contributions

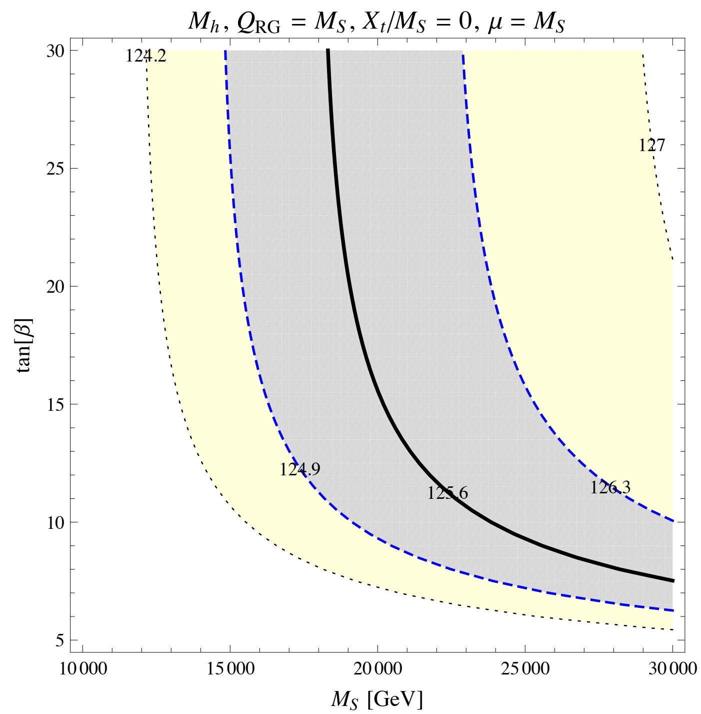
$$
\begin{aligned}
\delta_3\lambda = \Big\{ & -1728\lambda^4 - 3456\lambda^3 y_t^2 + \lambda^2 y_t^2(-576 y_t^2 + 1536 g_3^2) \\
& + \lambda y_t^2(1908 y_t^4 + 480 y_t^2 g_3^2 - 960 g_3^4) + y_t^4(1548 y_t^4 - 4416 y_t^2 g_3^2 + 2944 g_3^4)\Big\} L^3 \\
+ \Big\{ & -2340\lambda^4 - 3582\lambda^3 y_t^2 + \lambda^2 y_t^2(-378 y_t^2 + 2016 g_3^2) \\
& + \lambda y_t^2(1521 y_t^4 + 1032 y_t^2 g_3^2 - 2496 g_3^4) + y_t^4(1476 y_t^4 - 3744 y_t^2 g_3^2 + 4064 g_3^4)\Big\} L^2 \\
+ \Big\{ & -1502.84\lambda^4 - 436.5\lambda^3 y_t^2 - \lambda^2 y_t^2(1768.26 y_t^2 + 160.77 g_3^2) \\
& + \lambda y_t^2(446.764\lambda y_t^4 + 1325.73 y_t^2 g_3^2 - 713.936 g_3^4) \\
& + y_t^4(972.596 y_t^4 - 1001.98 y_t^2 g_3^2 + 200.804 g_3^4)\Big\} L,
\end{aligned}
$$

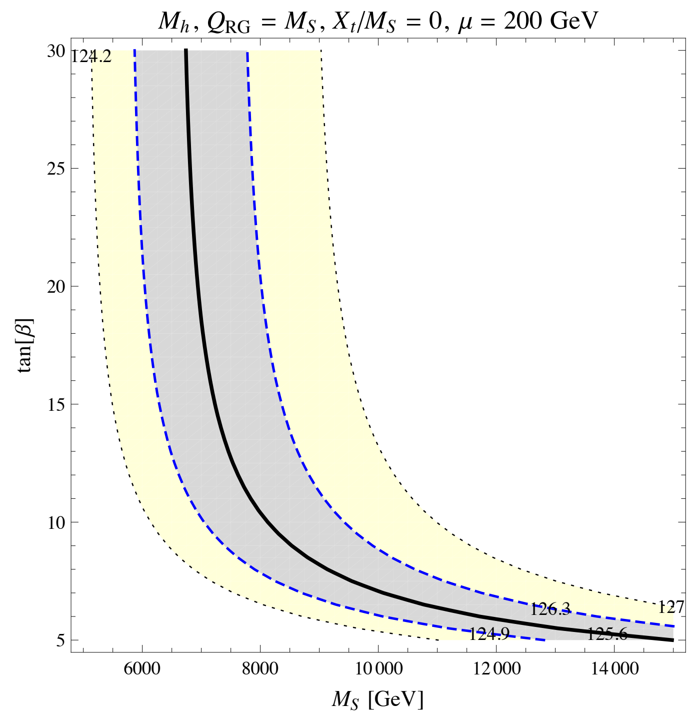
This is a SM effect, since this is the effective theory we are considering.

This shows that a partial computation of three loop effects is not justified

Draper, Lee, C.W. '13

Necessary stop mass values to get the proper Higgs mass for Small mixing in the stop sector

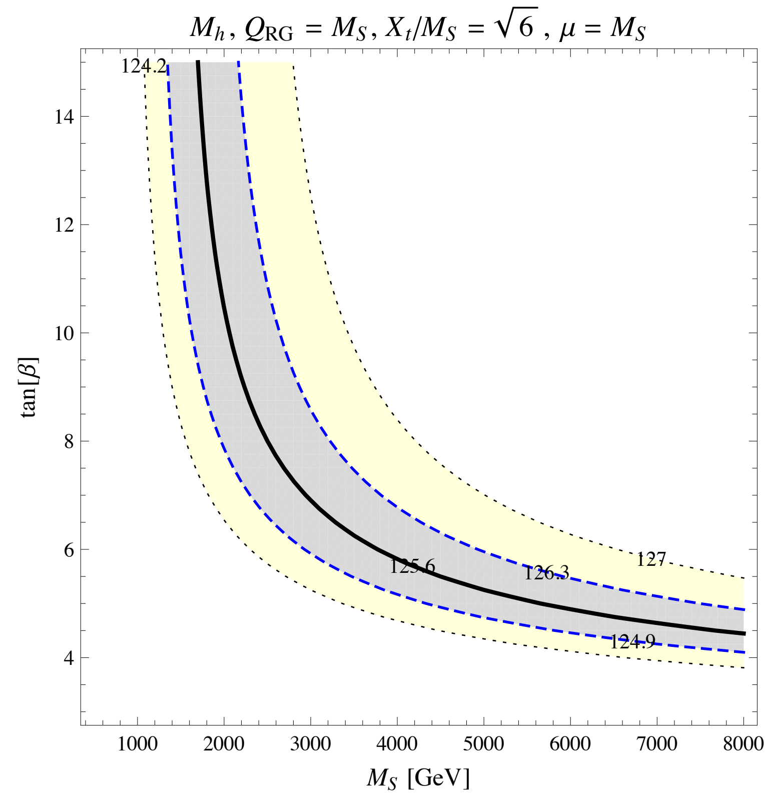


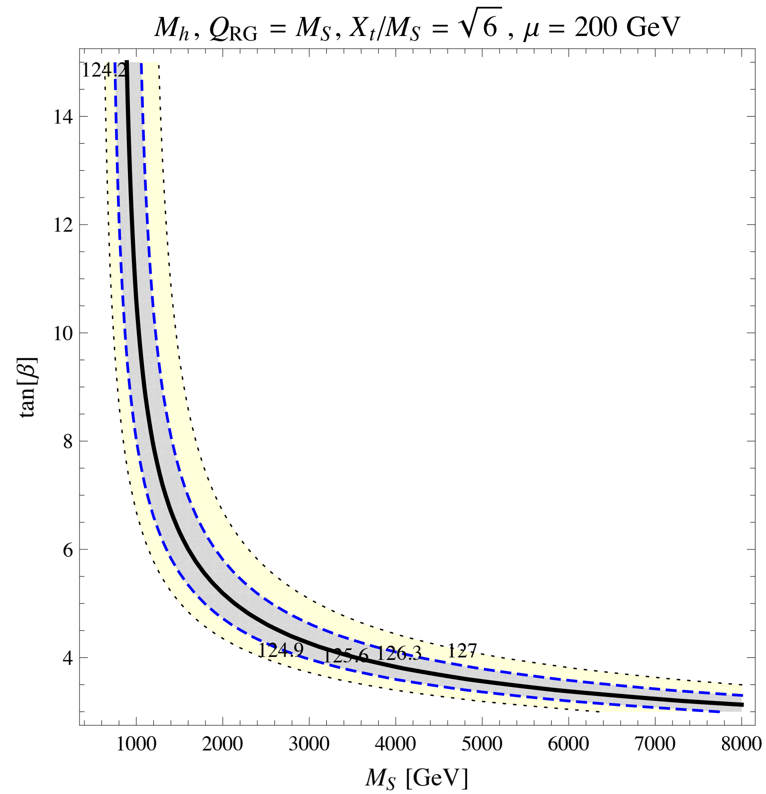


Such heavy stops would be out of the reach of the LHC
A higher energy collider necessary to investigate stop sector

Draper, Lee, C.W. '13

Necessary stop mass values to get the proper Higgs mass for Maximal mixing in the stop sector





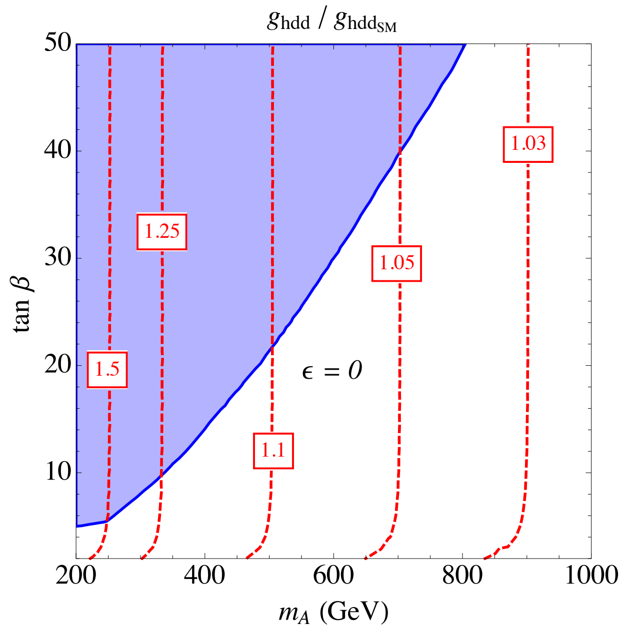
Light Stops at the reach of the LHC for large mixing in the Stop sector and moderate values of tanβ

Down Couplings in the MSSM for low values of μ

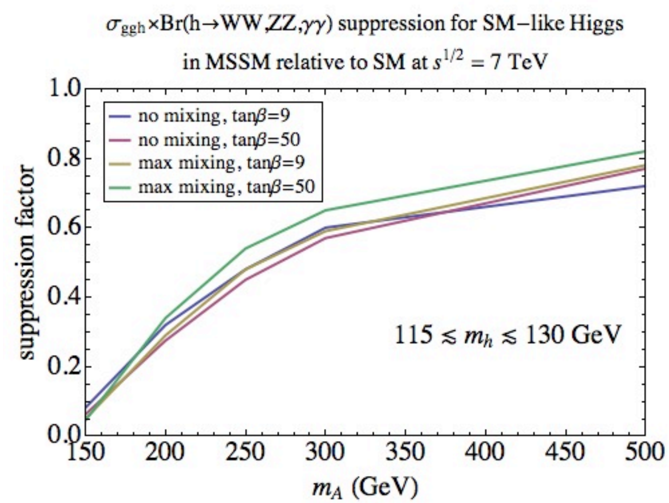
- In this regime, $\lambda_{6,7} \simeq 0$, and

$$\lambda_1 \simeq -\tilde{\lambda}_3 = \frac{g_1^2 + g_2^2}{4} = \frac{M_Z^2}{v^2} \simeq 0.125 \qquad\qquad \lambda^{\rm SM} \simeq 0.26$$

$$\lambda_2 \simeq \frac{M_Z^2}{v^2} + \frac{3}{8\pi^2} h_t^4 \left[\log\left(\frac{M_{\rm SUSY}^2}{m_t^2}\right) + \frac{A_t^2}{M_{\rm SUSY}^2}\left(1 - \frac{A_t^2}{12 M_{\rm SUSY}^2}\right)\right]$$



Carena, Low, Shah, C.W.'13

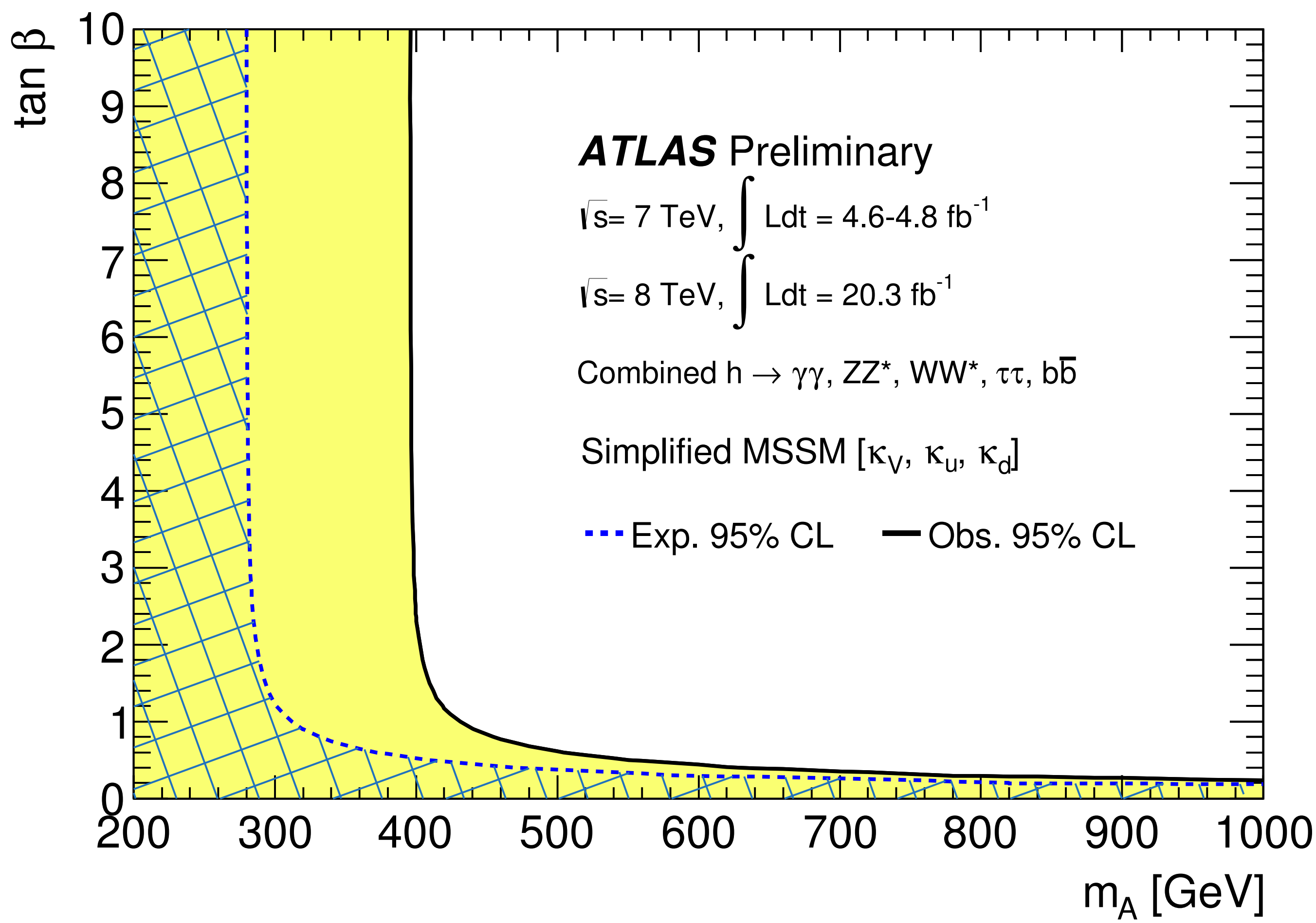


All vector boson branching ratios suppressed by enhancement of the bottom decay width

Enhancement of bottom quark and tau couplings independent of $\tan\beta$

Low values of μ similar to the ones analyzed by ATLAS

ATLAS-CONF-2014-010



Bounds coming from precision h measurements

Down Couplings in the MSSM for large values of μ

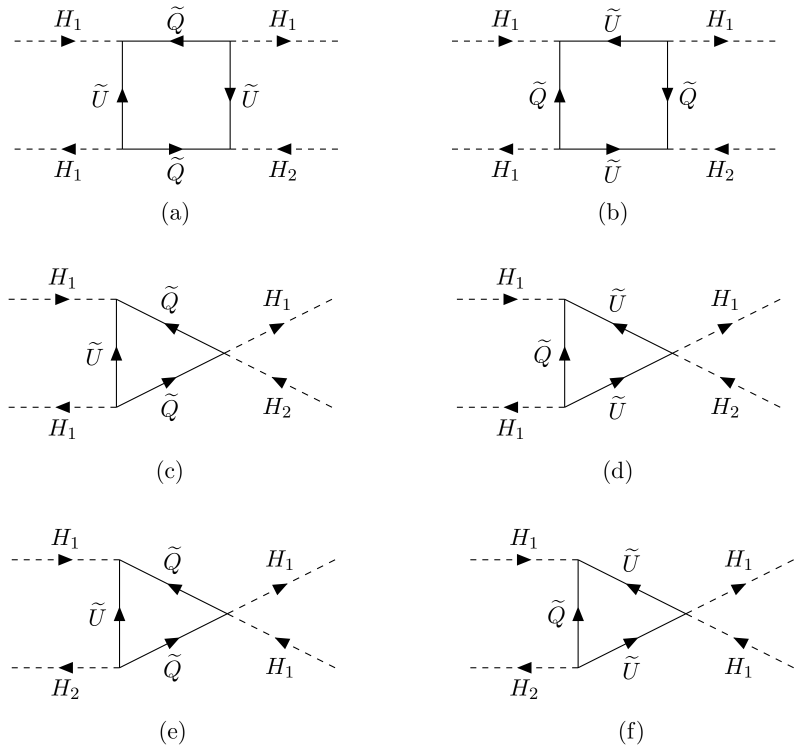
- At large values of μ, corrections to the quartic couplings $\lambda_{5,6,7}$ become significant.

- For nonvanishing values of these couplings, a new condition of alignment at large $\tan\beta$ is obtained

$$\tan\beta = \frac{\lambda_{\rm SM} - \tilde{\lambda}_3}{\lambda_7}, \qquad \lambda_2 \simeq \lambda_{\rm SM}$$

- Alignment for $\tan\beta \simeq 10$ may be obtained, making difficult the test of the "wedge" by coupling variations.

Higgs Basis



Haber and Gunion'02

$$H_1 = H_u \sin\beta + H_d \cos\beta$$
$$H_2 = H_u \cos\beta - H_d \sin\beta$$

In this basis, H_1 acquires a v.e.v., while H_2 does not. Alignment is obtained when quartic coupling $Z_6 H_1^3 H_2$ vanishes. H_1 and H_2 couple to stops with couplings

$$X_t = h_t \sin\beta\,(A_t - \mu/\tan\beta)$$
$$Y_t = h_t \cos\beta\,(A_t + \mu\tan\beta)$$

Carena, Haber, Low, Shah, C.W.'14

$$m_Z^2 c_{2\beta} = \frac{3v^2 s_\beta^2 h_t^4}{16\pi^2}\left[\ln\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t(X_t+Y_t)}{2M_S^2} - \frac{X_t^3 Y_t}{12 M_S^4}\right]$$

$$t_\beta = \frac{m_Z^2 + \frac{3v^2 h_t^4}{16\pi^2}\left[\ln\left(\frac{M_S^2}{m_t^2}\right) + \frac{2A_t^2 - \mu^2}{2M_S^2} - \frac{A_t^2(A_t^2 - 3\mu^2)}{12 M_S^4}\right]}{\frac{3v^2 h_t^4 \mu A_t}{32\pi^2 M_S^2}\left(\frac{A_t^2}{6M_S^2} - 1\right)}$$

One recovers the previous expression, while replacing the SM-like coupling λ2 by the expression given before.

M. Carena, I. Low, N. Shah, C.W.'13

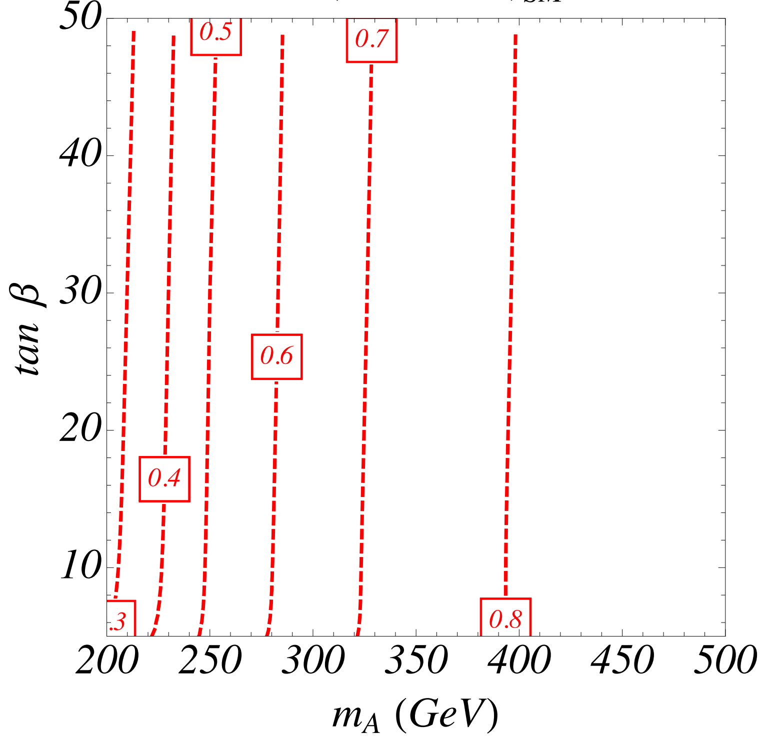
Carena, Haber, Low, Shah, C.W.'14

Higgs Decay into Gauge Bosons

Mostly determined by the change of width

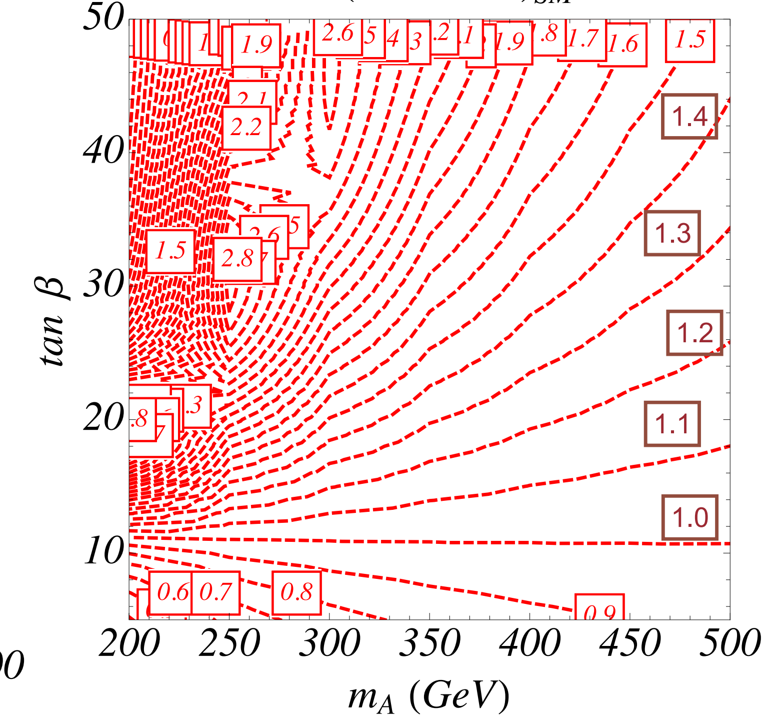
Small μ

$$\frac{BR\,(h\,\rightarrow\,WW)}{BR\,(h\,\rightarrow\,WW)_{SM}}$$



$\mu/M_{\rm SUSY} = 2, \quad A_t/M_{\rm SUSY} \simeq 3$

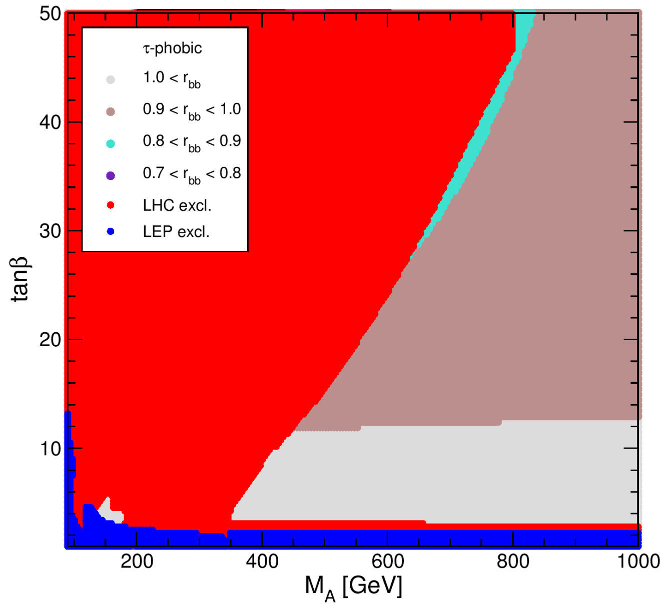
$$\frac{BR\,(h\,\rightarrow\,WW)}{BR\,(h\,\rightarrow\,WW)_{SM}}$$

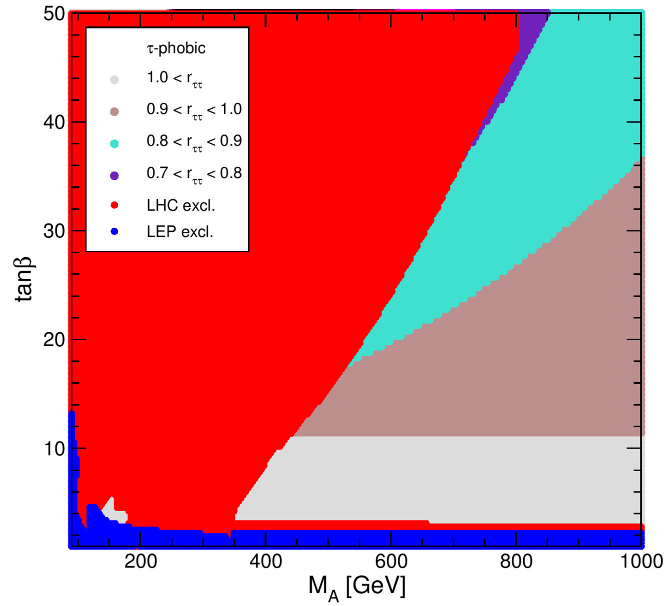


CP-odd Higgs masses of order 200 GeV and tanβ = 10 OK in the alignment case

The Alignment (τ-phobic) scenario

Suppression of down-type fermion couplings to the Higgs due to Higgs mixing effects. Staus play a relevant role. Decays into staus relevant for heavy non-standard Higgs bosons.





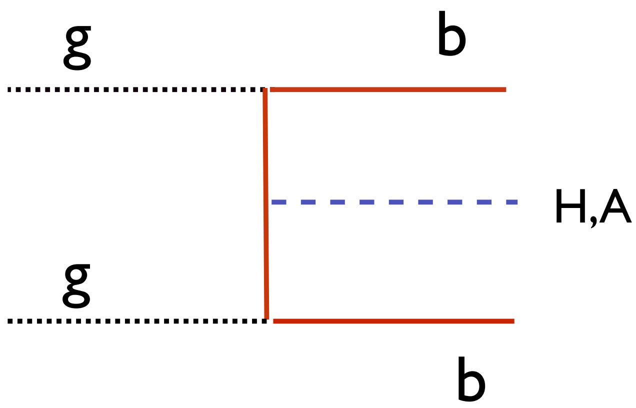
$$
\begin{aligned}
M_{\rm SUSY} &= 1500 \text{ GeV}, \\
\mu &= 2000 \text{ GeV}, \\
M_2 &= 200 \text{ GeV}, \\
X_t^{\rm OS} &= 2.45\, M_{\rm SUSY} \text{ (FD calculation)}, \\
X_t^{\overline{\rm MS}} &= 2.9\, M_{\rm SUSY} \text{ (RG calculation)}, \\
A_b &= A_\tau = A_t\ , \\
m_{\tilde{g}} &= 1500 \text{ GeV}, \\
M_{\tilde{l}_3} &= 500 \text{ GeV}\ .
\end{aligned}
$$

M. Carena, S. Heinemeyer, O. Stål, C.E.M. Wagner, G. Weiglein, arXiv:1302.7033

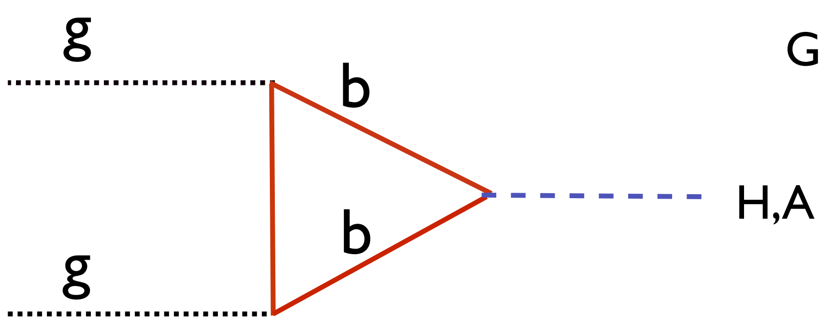
$$
{\rm Loop}_{12} = \frac{m_t^4}{16\pi^2 v^2 \sin^2\beta} \frac{\mu \tilde{A}_t}{M_{\rm SUSY}^2} \left[\frac{A_t \tilde{A}_t}{M_{\rm SUSY}^2} - 6 \right] + \frac{h_b^4 v^2}{16\pi^2} \sin^2\beta \frac{\mu^3 A_b}{M_{\rm SUSY}^4} + \frac{h_\tau^4 v^2}{48\pi^2} \sin^2\beta \frac{\mu^3 A_\tau}{M_{\tilde{\tau}}^4}
$$

Non-Standard Higgs Production

QCD: S. Dawson, C.B. Jackson, L. Reina, D.Wackeroth, hep-ph/06031



Associated Production



Gluon Fusion

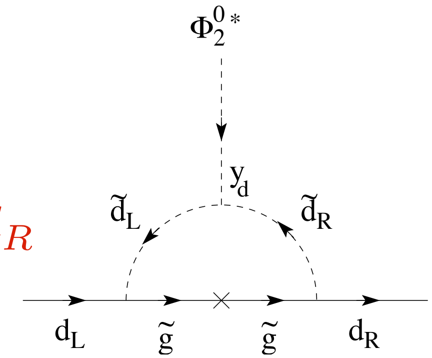
$$g_{Abb} \simeq g_{Hbb} \simeq \frac{m_b \tan\beta}{(1+\Delta_b)v}, \qquad g_{A\tau\tau} \simeq g_{H\tau\tau} \simeq \frac{m_\tau \tan\beta}{v}$$

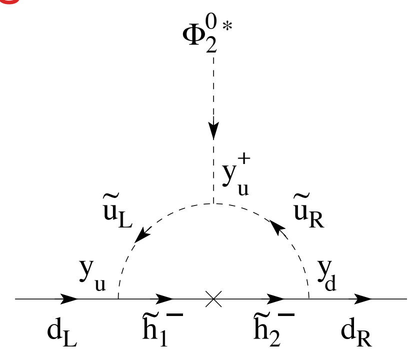
Hempfling '93
Hall, Rattazzi, Sarid'93
Carena, Olechowski, Pokorski, C.W.'93

Radiative Corrections to Flavor Conserving Higgs Couplings

- Couplings of down and up quark fermions to both Higgs fields arise after radiative corrections.

$$\mathcal{L} = \bar{d}_L (h_d H_1^0 + \Delta h_d H_2^0) d_R$$





- The radiatively induced coupling depends on ratios of supersymmetry breaking parameters

$$m_b = h_b v_1 \left(1 + \frac{\Delta h_b}{h_b} \tan\beta\right)$$

$$\boxed{\tan\beta = \frac{v_2}{v_1}}$$

$$\frac{\Delta_b}{\tan\beta} = \frac{\Delta h_b}{h_b} \simeq \frac{2\alpha_s}{3\pi} \frac{\mu M_{\tilde{g}}}{\max(m_{\tilde{b}_i}^2, M_{\tilde{g}}^2)} + \frac{h_t^2}{16\pi^2} \frac{\mu A_t}{\max(m_{\tilde{t}_i}^2, \mu^2)}$$

$$X_t = A_t - \mu/\tan\beta \simeq A_t \qquad \Delta_b = (E_g + E_t h_t^2) \tan\beta$$

Resummation : Carena, Garcia, Nierste, C.W.'00

Searches for non-standard Higgs bosons

M. Carena, S. Heinemeyer, G.Weiglein,C.W, EJPC'06

- Searches at the Tevatron and the LHC are induced by production channels associated with the large bottom Yukawa coupling.

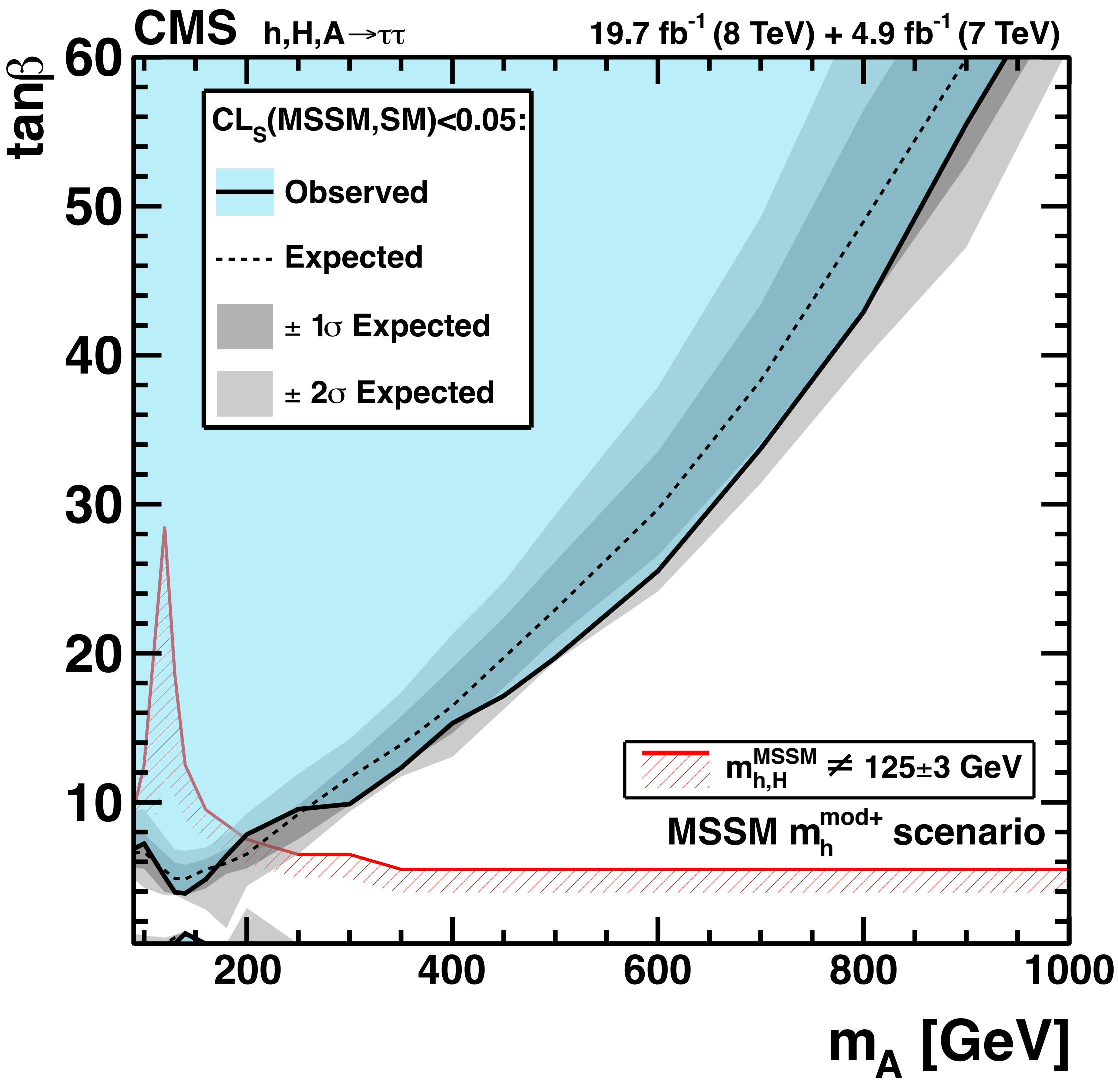
$$\sigma(b\bar{b}A) \times BR(A \to b\bar{b}) \simeq \sigma(b\bar{b}A)_{\rm SM} \frac{\tan^2\beta}{(1+\Delta_b)^2} \times \frac{9}{(1+\Delta_b)^2 + 9}$$

$$\sigma(b\bar{b}, gg \to A) \times BR(A \to \tau\tau) \simeq \sigma(b\bar{b}, gg \to A)_{\rm SM} \frac{\tan^2\beta}{(1+\Delta_b)^2 + 9}$$

- There may be a strong dependence on the parameters in the bb search channel, which is strongly reduced in the tau tau mode.

- If charginos are light, they contribute to the total with, suppressing the BR.

$$\sigma(pp \to H, A \to \tau\tau) \propto \frac{\tan^2\beta}{\left[\left(3\frac{m_b^2}{m_\tau^2} + \frac{(M_W^2+M_Z^2)(1+\Delta_b)^2}{m_\tau^2\tan^2\beta}\right)(1+\Delta_\tau)^2 + (1+\Delta_b)^2\right]}$$



How to test the region of low tanbeta and moderate mA ?

Decays of non-standard Higgs bosons into paris of standard ones, charginos and neutralinos may be a possibility.

Can change in couplings help there ?

It depends on radiative corrections

We shall assume light gauginos, $M_2 = 2\ M_1 \simeq 200$ GeV.

This is an example of a low μ scenario

$$A_t \simeq 1.5\ M_{\rm SUSY}, \quad \mu = 200\ \rm GeV$$

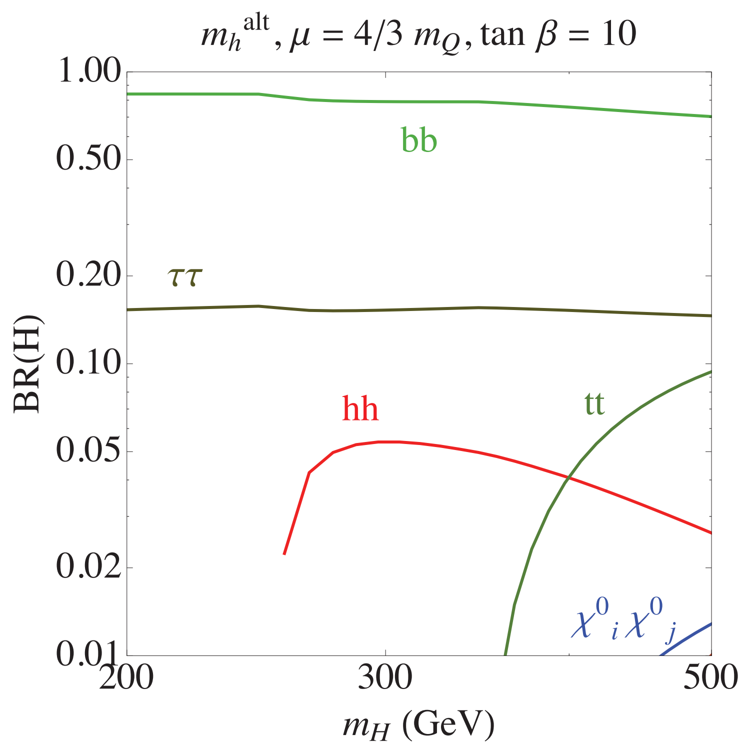
At low values of $\tan\beta$, the SUSY mass scale must be raised.

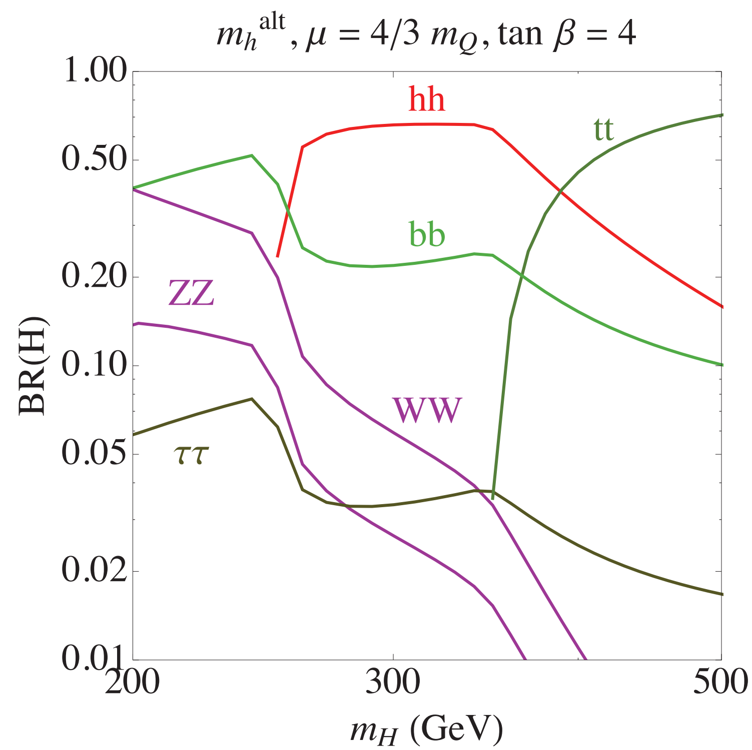
Heavy Supersymmetric Particles

Heavy Higgs Bosons : A variety of decay Branching Ratios

Carena, Haber, Low, Shah, C.W.'14

Depending on the values of μ and tanβ different search strategies must be applied.



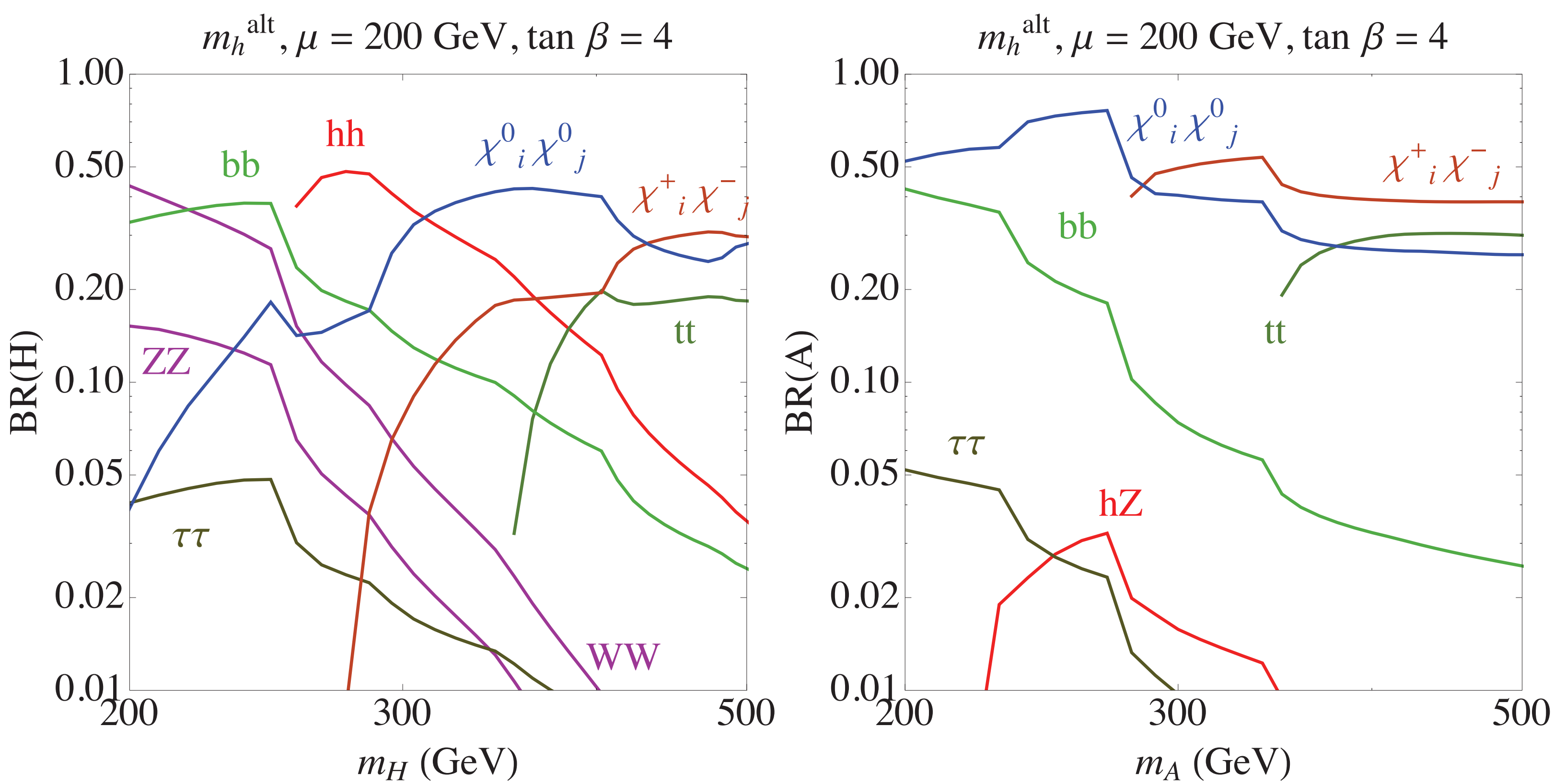


At large tanβ, bottom and tau decay modes dominant.

As tanβ decreases decays into SM-like Higgs and wek bosons become relevant

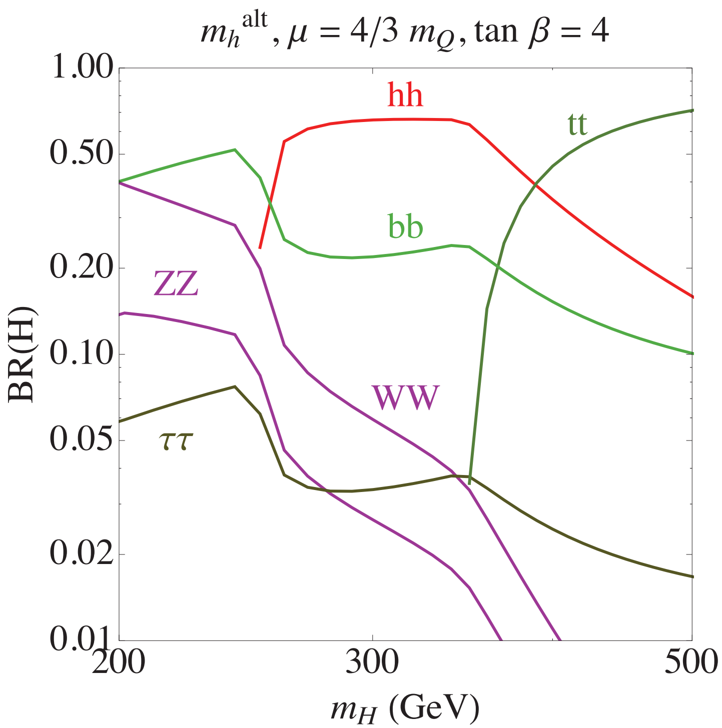
Light Charginos and Neutralinos can significantly modify M the CP-odd Higgs Decay Branching Ratios

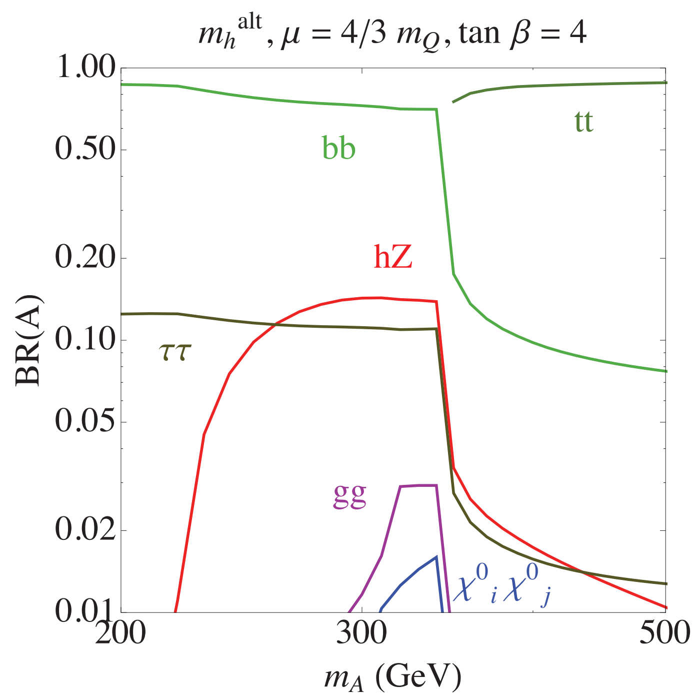
Carena, Haber, Low, Shah, C.W.'14



At small values of tanβ, and small μ, heavy Higgs decay into top quarks and electroweakinos become dominant. Still, decays into pairs of Higgs very relevant.

Large μ and small tanβ



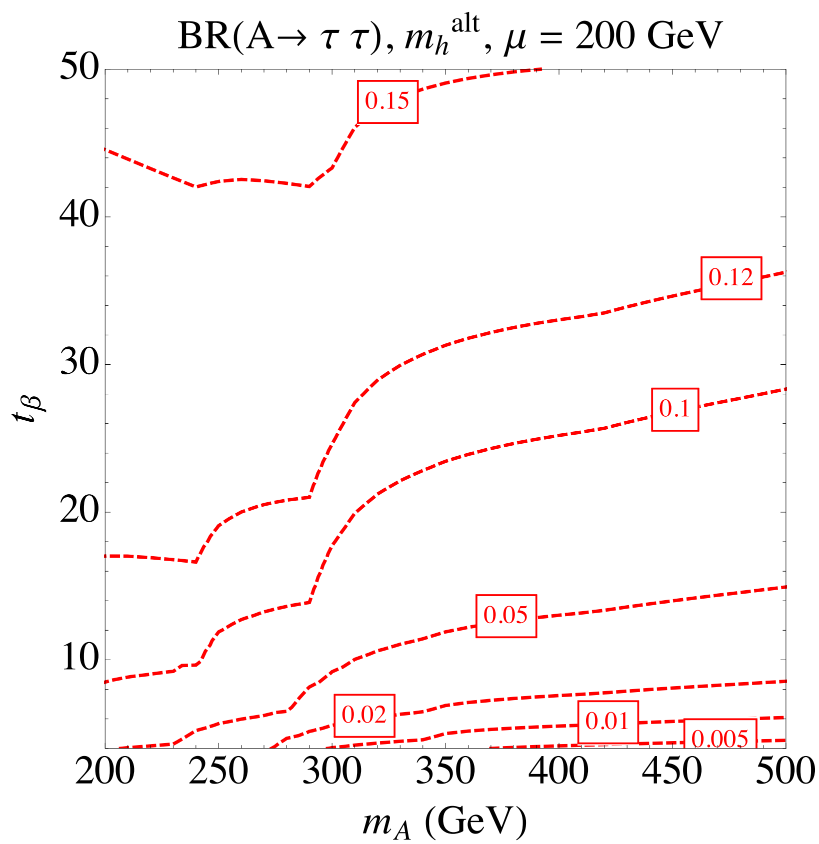


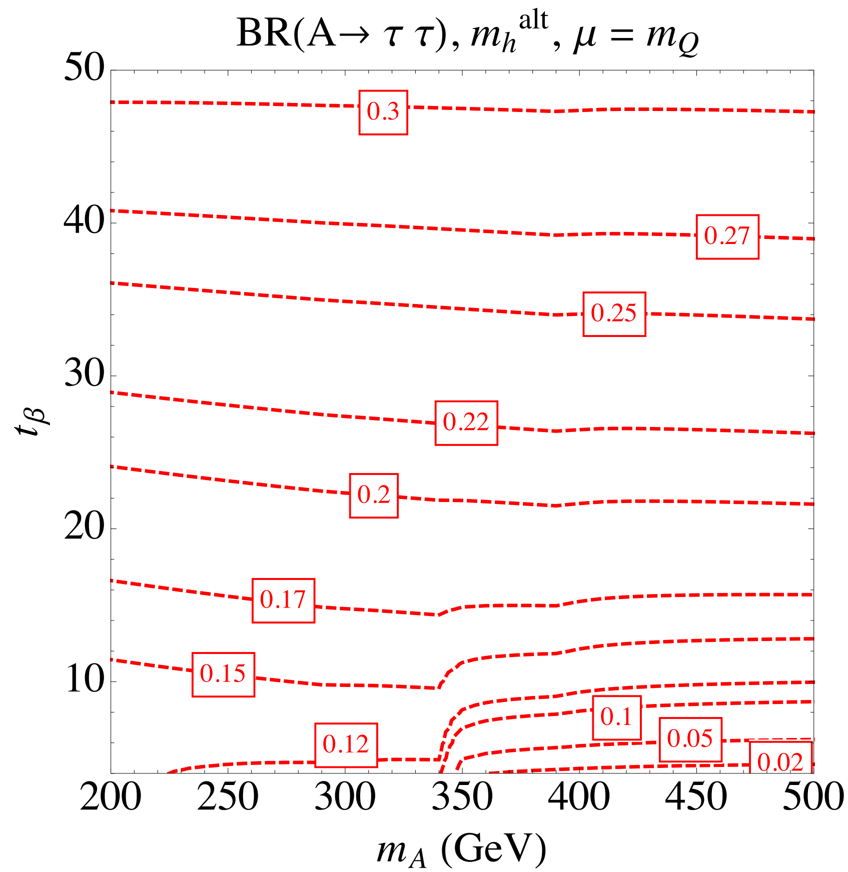
Decays into gauge and Higgs bosons become important also for the CP-odd Higgs

Carena, Haber, Low, Shah, C.W.'14

Variation of the CP-odd Higgs Decays with the value of μ

Strong suppression due to chargino contribution

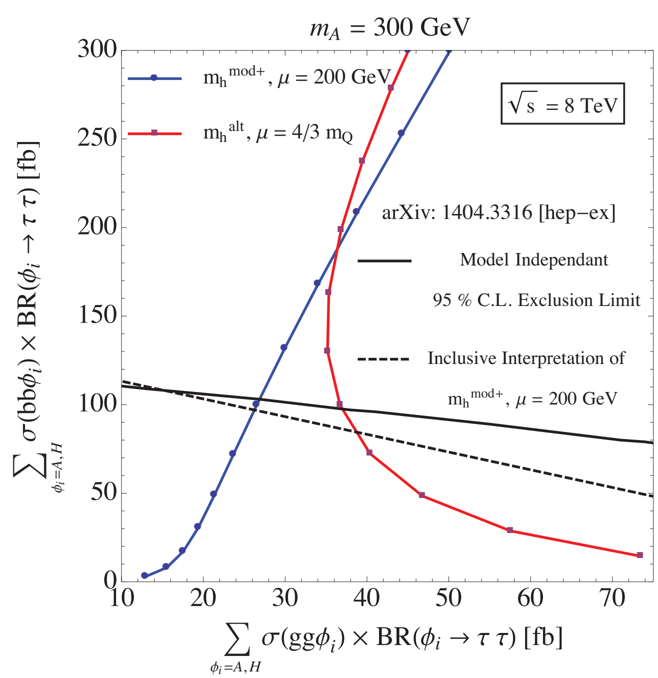




Decays into taus become prominent for heavy electroweakino masses (or suppressed couplings)

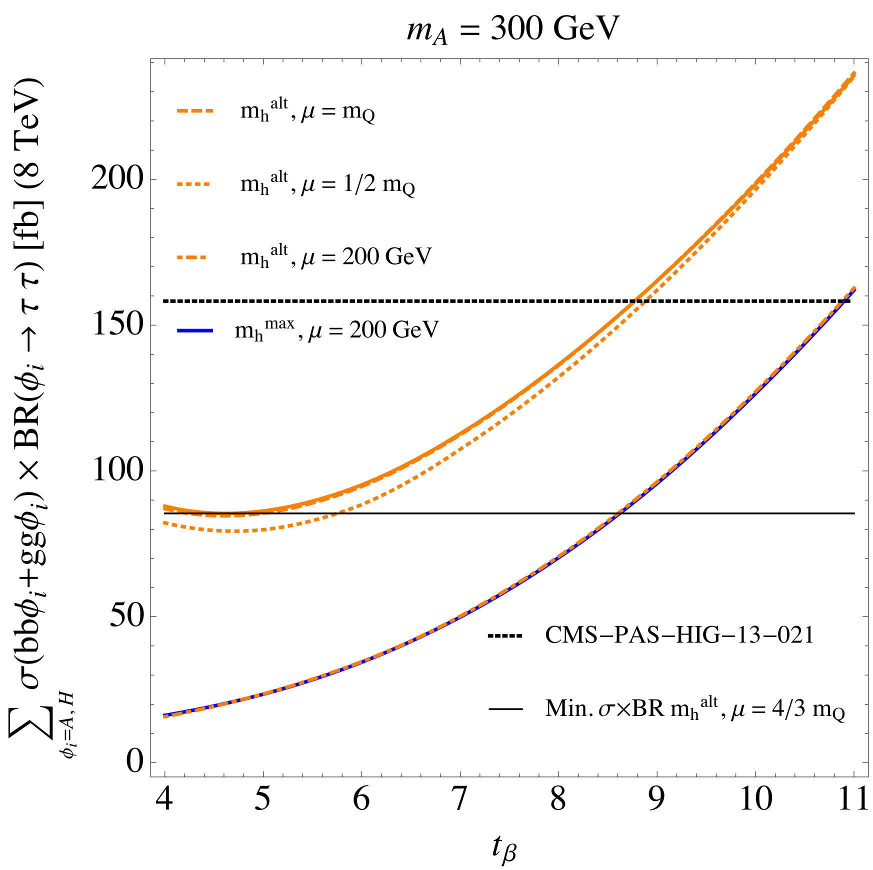
Bounds from Direct heavy Higgs searches

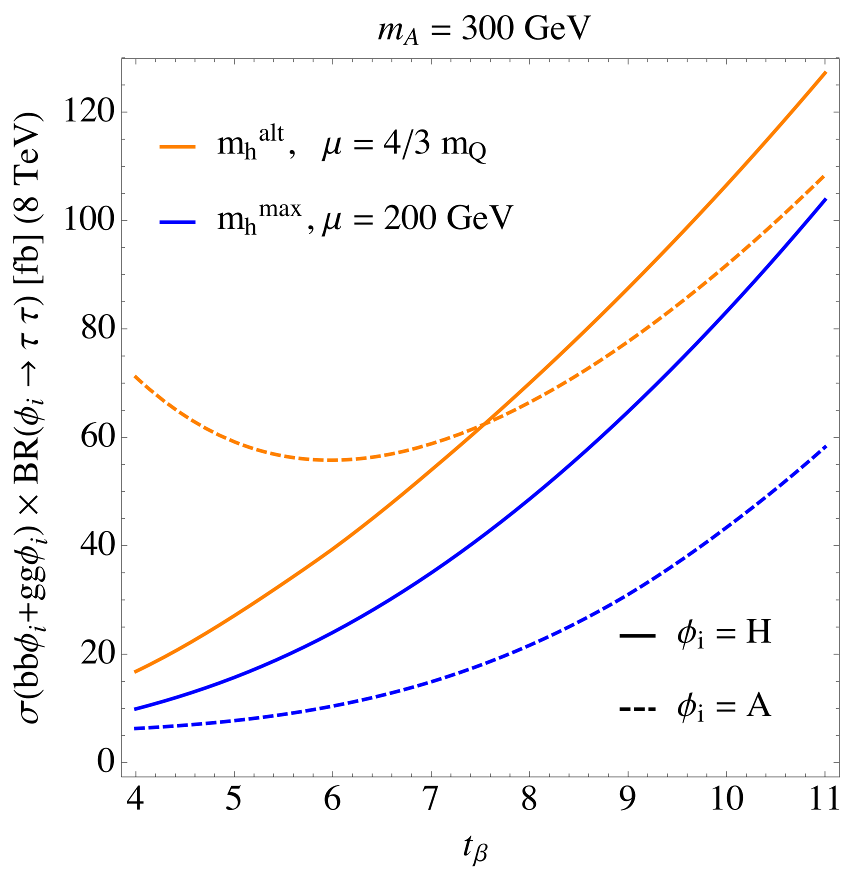
- Most important bounds at 8 TeV come from searches of Higgs decays into τ-leptons and b-quarks
- Production cross section comes from gluon fusion and associated production with bottom quarks
- They have a different behavior with tanβ. Model indpendent bounds obtained by LHC collaborations and can be used.
- Similar bounds obtained from inclusive production of τ pairs.



Change in bound of tan β due to variation of μ

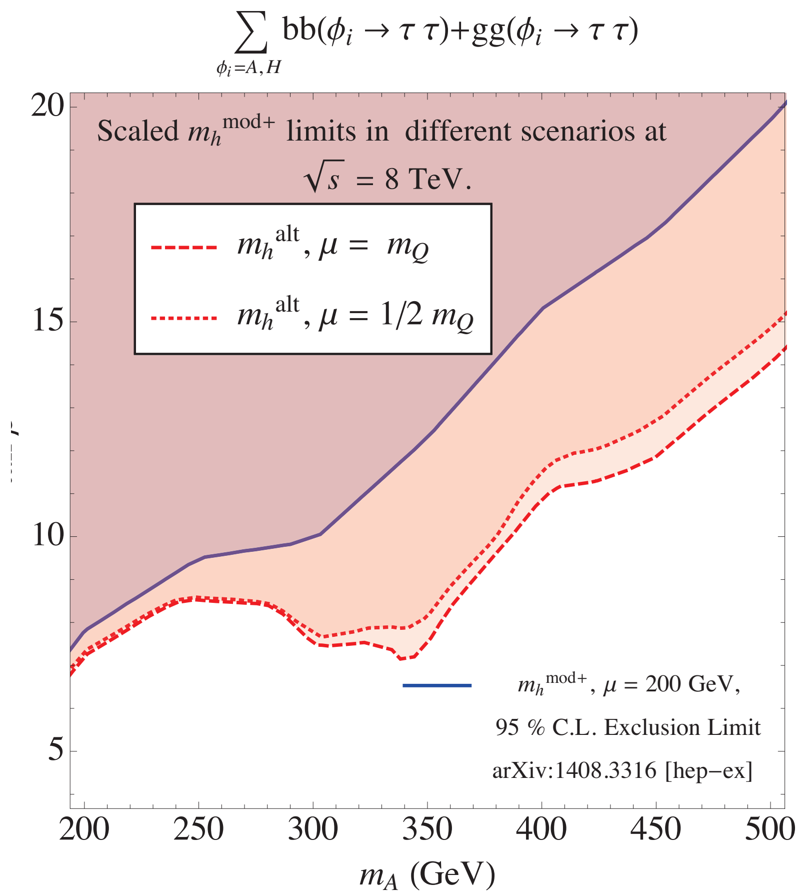
Carena, Haber, Low, Shah, C.W.'14





Variation of the Experimental Bound with the value of μ

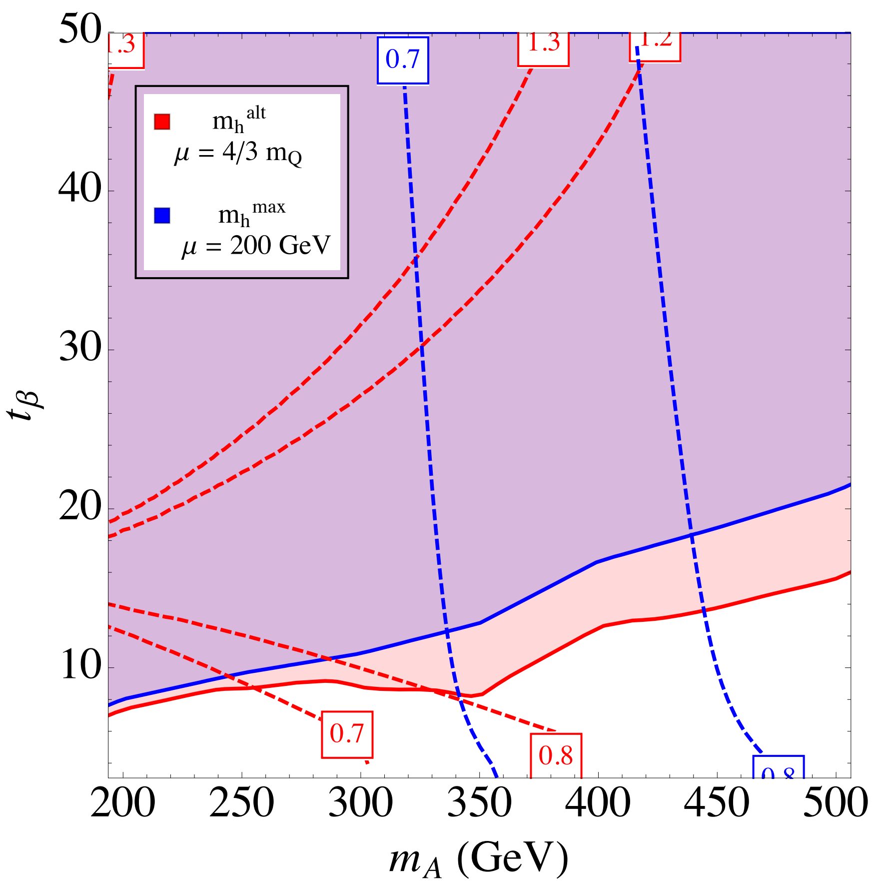
Carena, Haber, Low, Shah, C.W.'14



The bound becomes stronger at large values of μ, due to the increase in the τ decay branching ratio

Complementarity between different search channels

Carena, Haber, Low, Shah, C.W.'14



— $\sum_{\phi_i = A, H} \sigma(bb\phi_i + gg\phi_i) \times BR(\phi_i \to \tau\,\tau)$ (8 TeV)

--- $\sigma(bbh + ggh) \times BR(h \to VV)/SM$

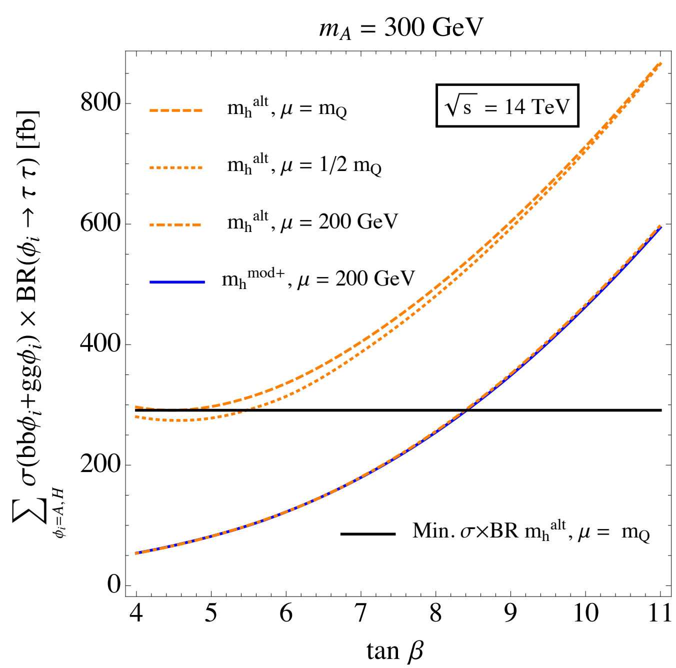
Limits coming from measurements of h couplings become weaker for larger values of μ

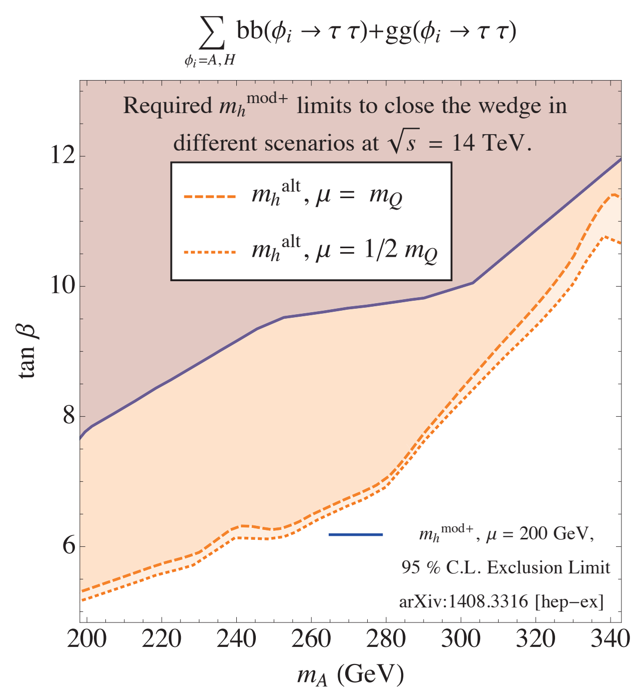
Limits coming from direct searches of $H, A \to \tau\tau$ become stronger for larger values of μ

Bounds on m_A are therefore dependent on the scenario and at present become weaker for larger μ

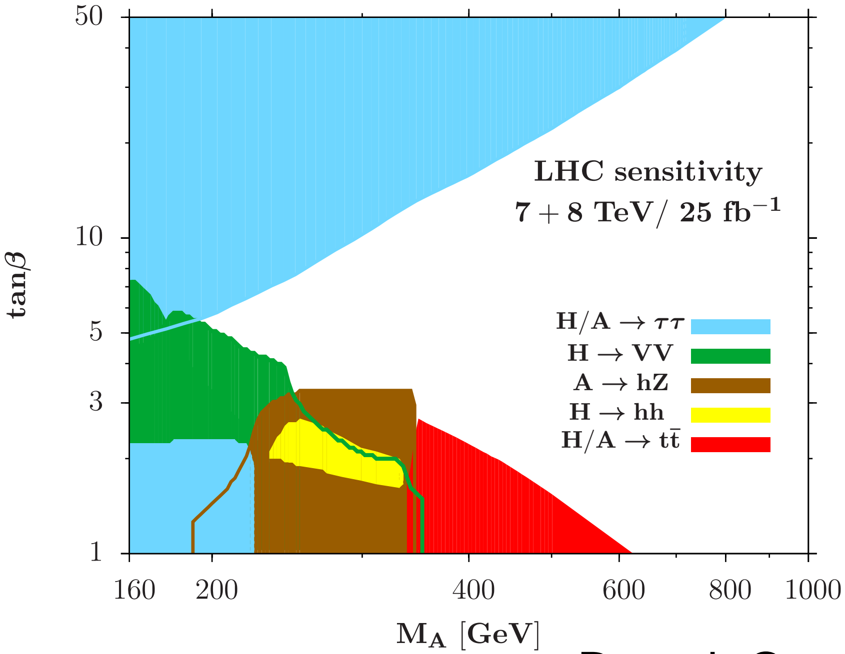
With a modest improvement of direct search limit one would be able to close the wedge, below top pair decay threshold

Limit in the mhmax scenario that would close the wedge for masses below 350 GeV



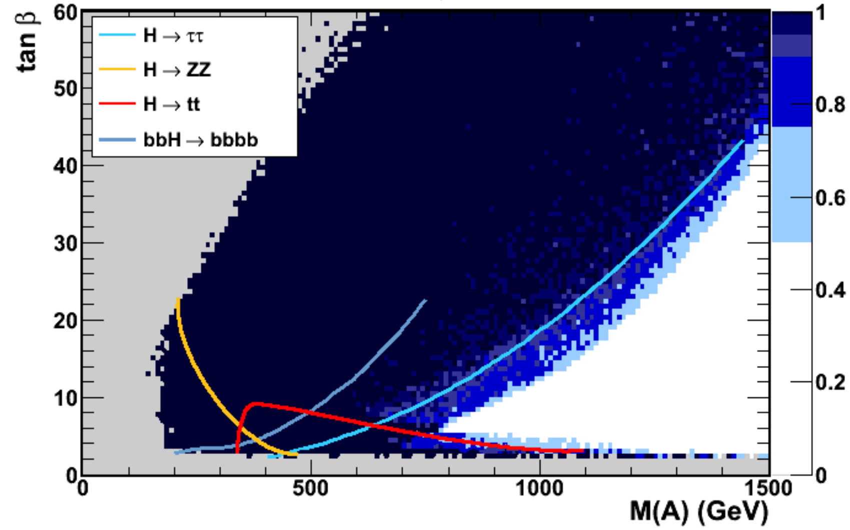


Reach in different channels. Energy Dependence

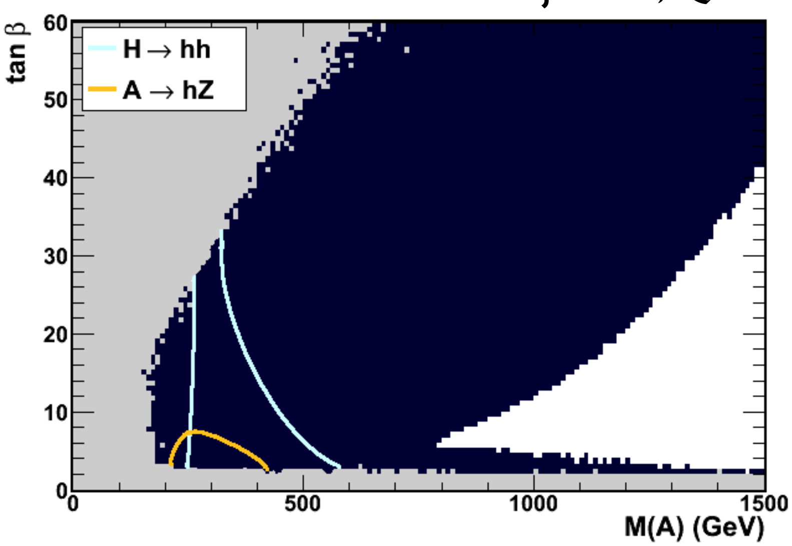


Djouadi, Quevillon'13

14 TeV, 150 fb^{-1}



Arbey, Battaglia, Mahmoudi'13



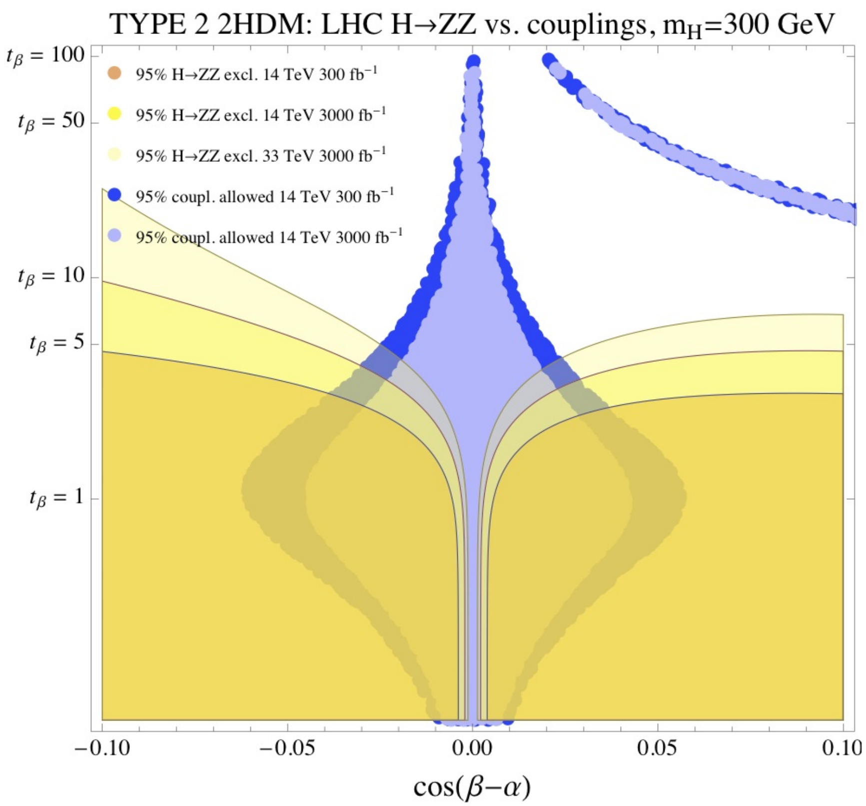
14 TeV, 150 fb^{-1}

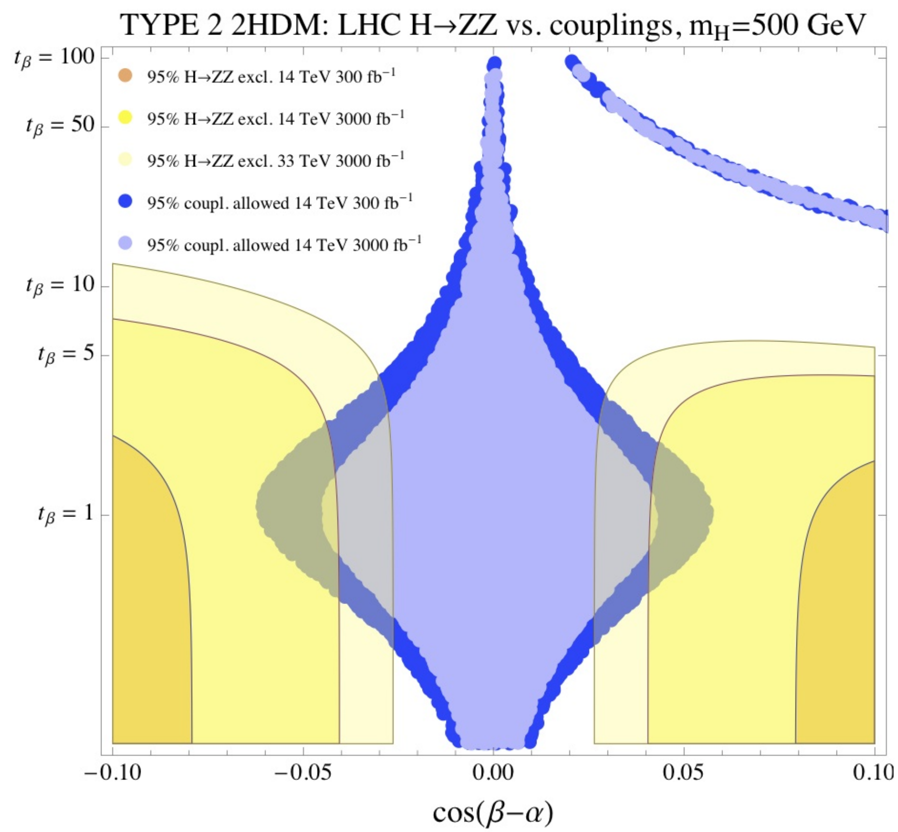
These latest channels are only open away from the Alignment region. Here μ is mostly sizable, but sufficiently small so alignment not obtained

Reach with increasing Energy

Two sigma Exclusion limits

$$-\frac{\sin\alpha}{\cos\beta} = \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha) \qquad \cos(\beta-\alpha) \simeq \sin\beta\cos\beta\frac{m_h^2 - m_Z^2\cos 2\beta}{m_A^2\sin^2\beta + M_Z^2\cos^2\beta - m_h^2}$$

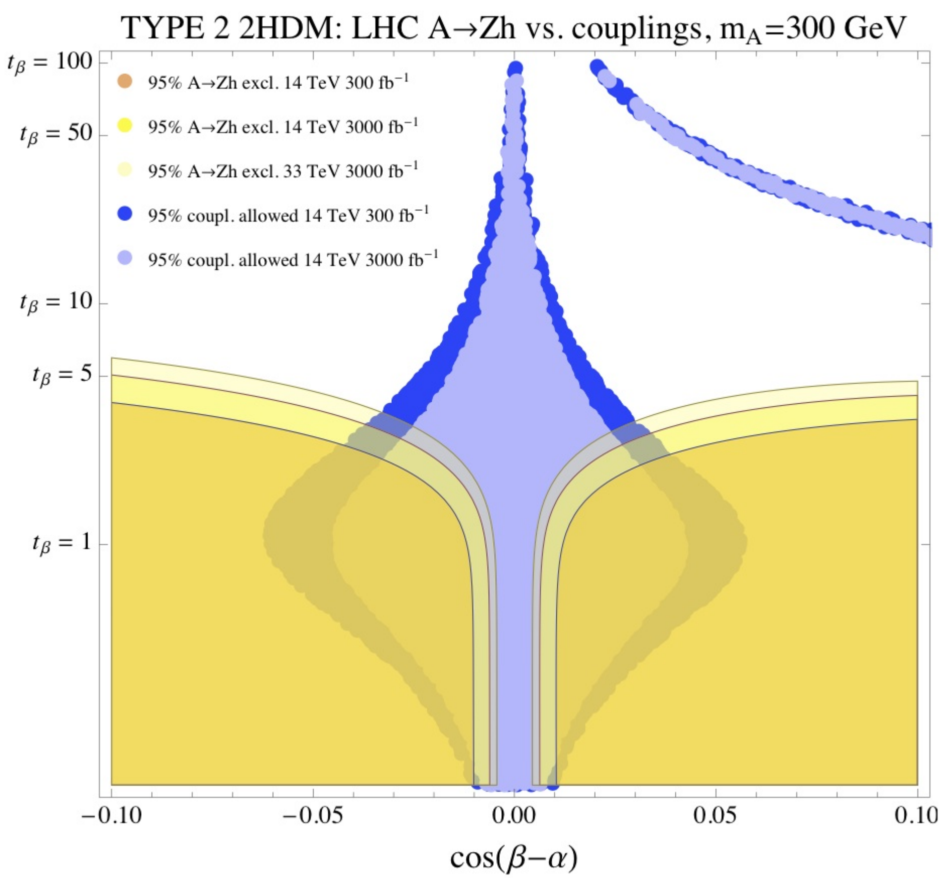


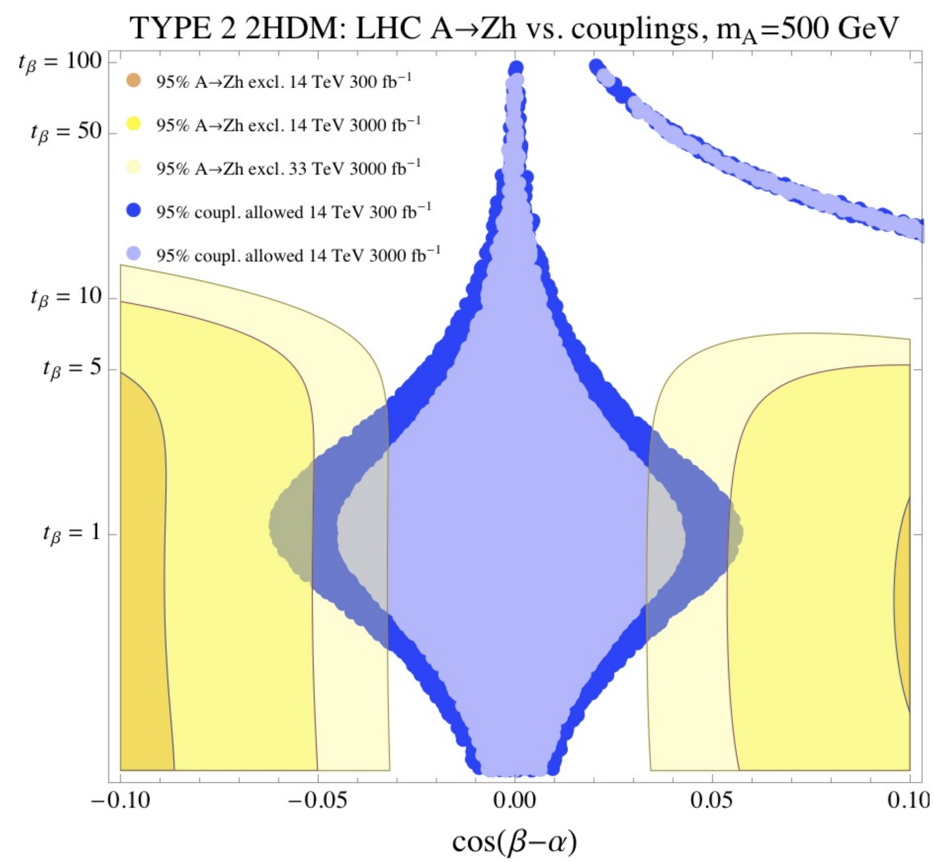


Browson et al'13

Reach with increasing Energy

Two sigma Exclusion limits





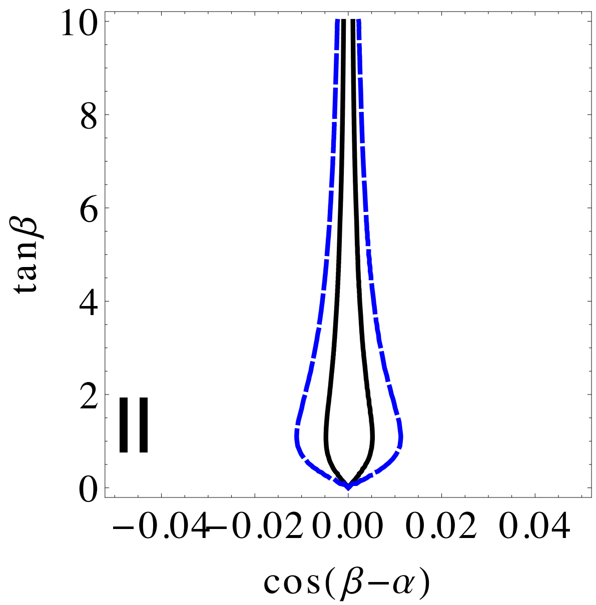
Browson et al'13

Comparison of 14 TeV with 100 TeV

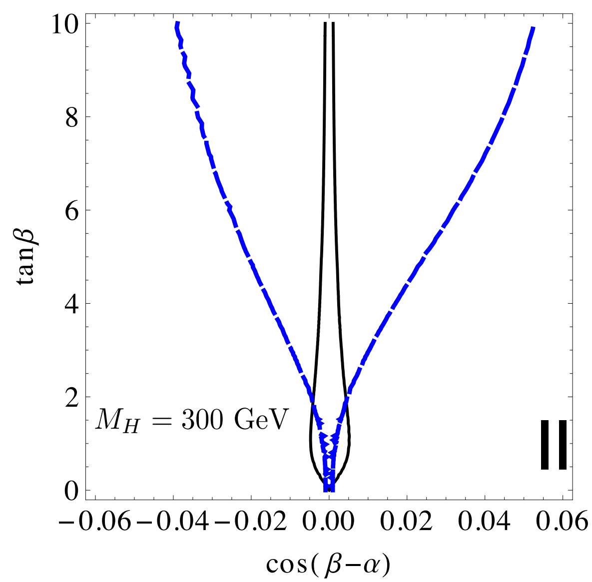
Black solid: 100 TeV, L=1/ab

Blue dashed: 14 TeV, L=3/ab

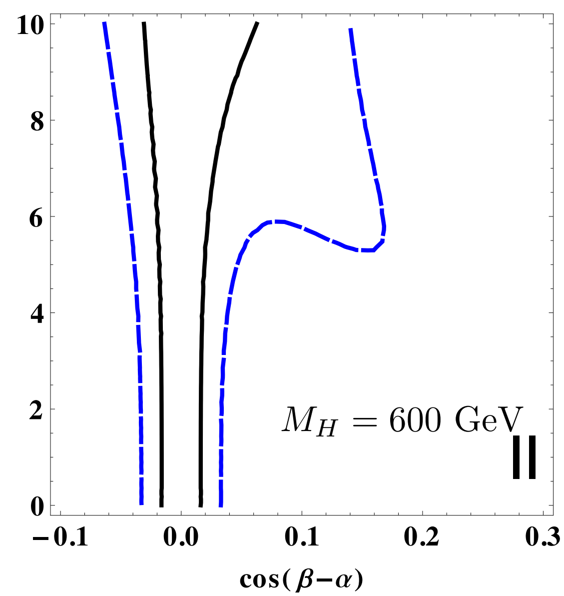
Chien-Yi Chen, SLAC Workshop, 04.14



Precision h Measurements



Comparison of precision Measurements and direct H to WW, ZZ searches



Direct H to WW,ZZ searches

Conclusions

- The MSSM provides a very predictive framework for the computation of the Higgs phenomenology.
- The properties of the lightest and heavy Higgs bosons depend strongly on radiative corrections mediated by the stops
- In general, at low values of the CP-odd Higgs mass the lightest CP-even Higgs width increases, leading to a suppression of the other decay branching ratios (with the possible exception of loop induced couplings)
- Such suppressions are restricted by present measurements, and can only be avoided under the presence of alignment.
- Alignment in the MSSM appears for large values of mu, for which decays into electroweakinos are suppressed, making the bounds coming from decays into SM particles stronger.
- Bounds on the CP-odd Higgs mass are model dependent and should take into account this dependence.
- Complementarity between precision measurements and direct searches will allow to probe efficiently the MSSM Higgs sector

Comparison of BR of decay into vector bosons and photons